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ICHNOLOGY, SEDIMENTOLOGY AND STRATIGRAPHY OF THE LOWER CRETACEOUS VIKING FORMATION AT MIKWAN, FENN AND CHAIN, ALBERTA, CANADA

BY

JEFFREY CRAIG PETERSON

A THESIS SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF GEOLOGY

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FACULTY OF GRADUATE STUDIES AND RESEARCH

THE UNDERSIGNED CERTIFY THAT THEY HAVE READ, AND RECOMMEND TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH FOR ACCEPTANCE, A THESIS ENTITLED **ICHNOLOGY, SEDIMENTOLOGY AND STRATIGRAPHY OF THE LOWER CRETACEOUS VIKING FORMATION AT MIKWAN, FENN, AND CHAIN, ALBERTA, CANADA,** SUBMITTED BY JEFFREY CRAIG PETERSON IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

ABSTRACT

Siliciclastic facies from the Lower Cretaceous (Albian) Viking Formation in Townships 32-38, Ranges 16-24W4 were studied in detail. Over 37 cores and 470 geophysical well logs were examined and four cross-sections and seven maps demonstrate the lateral and vertical relationships of the facies within the study area. Ichnology is integrated with physical sedimentology and stratigraphy in order to resolve the depositional history of the Viking Fm in the study area.

The Viking Fm in the study area can be differentiated into 13 facies, which are arranged into five recurring facies associations (designated FA1, FA2, FA3, FA4 and FA5). Facies associations are separated by 5 discontinuities of sequence stratigraphic importance. The lowermost facies association (FA1) consists of a progradational parasequence set of the Highstand System Tract and is representative of Regional Viking deposits. A relative sea level fall, followed by transgressive ravinement, generated Discontinuity 3, which incised into FA1, and is interpreted to be an almagamated flooding surface/sequence boundary (FS/SB). Fully marine shoreface deposits comprising FA2 overlie Discontinuity 3 and constitute an incised shoreface complex deposited during a stillstand in transgression. A fall in relative sea level, followed by transgression, led to the incision of Discontinuity 2 into FA2. Discontinuity 2 is interpreted to be a FS/SB. Facies of FA3 overlie Discontinuity 2, and differ markedly from those of FA1 and FA2. FA3 is dominated by coarse-grained, trough cross-bedded sandstones containing mudstone interbeds, mudstone interlaminae and mudstone rip-up clasts interstratified with interbedded mudstones and sandstones. These facies contain a low diversity trace fossil suite, interpreted to be salinity-stressed. The coarse-grained facies of FA3 are interpreted have been deposited by tidal creeks and channels feeding fluvially-transported clastics into a sheltered embayment producing a coarse clastic "apron". The interbedded mudstones and sandstones correspond to sheltered embayment deposits. Resumption of transgression led to the development of a ravinement surface designated Discontinuity 1 which rises landward in a "step-wise" fashion. Fully marine, offshore deposits of FA4 overlie Discontinuity 1. A regional fall in relative sea level followed by incremental transgression led to formation of the regionally extensive VE4 surface. VE4 is overlain by conglomerates and sandstones of FA5. A resumption of transgression generated the Colorado flooding surface which caps the Viking Fm deposits in the study area and heralded the deposition of the marine shales of the Westgate Fm.

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LIST OF ABBREVIATIONS

D1-Discontinuity One
D2-Discontinuity Two
D3-Discontinuity Three
FA-Facies Association
FA1-Facies Association One
FA2-Facies Association Two
FA3-Facies Association Three
FA4-Facies Association Four
FA5-Five Association Five
Fig.-Figure
Figs.-Figures
Fm-Formation
FS/SB- Flooding Surface/Sequence Boundary
LM1-Log Marker One
LM2-Log Marker Two
LSE-Lowstand Surface of Erosion
TSE-Transgressive Surface of Erosion
VE4-Viking Erosion Surface Four

CHAPTER 1: INTRODUCTION, STUDY AREA, OBJECTIVE, METHODOLOGY, STRATIGRAPHY, PALEOGEOGRAPHY, STRUCTURAL SETTING AND PREVIOUS WORK

1.1 Introduction

The Lower Cretaceous Viking Formation in south-central Alberta has long been a prolific hydrocarbon producer, and as such, the object of great commercial and academic interest. According to Energy Resources Conservation Board data, the Viking Formation in Alberta has initial recoverable reserves of 88.7 x 10^6 m^3 of oil and 227.9 x 10^9 m^3 of natural gas (ERCB, 1990). Most of the commercial discoveries in the Viking Formation occurred in the 1950s and 1960s. Subsequently it was considered a mature play and interest waned until the discovery of the Viking Crystal Field in 1978. The discovery of Crystal, along with the advent of sequence stratigraphic analysis, has led to a revival of academic and commercial interest in the Viking Fm. Work has lately focused on putting the Viking Fm into a sequence stratigraphic or allostratigraphic framework (cf. Boreen and Walker, 1991; Posamentier and Chamberlain 1991a; Pattison, 1991a; Davies and Walker, 1993).

Recent studies of Viking Fm deposits focus on the recognition and delineation of erosional discontinuities in the Viking Fm. This information can be used to decipher the record of relative sea level change and erect a high resolution stratigraphic framework for the Viking Fm. However, most workers have characterized Viking Fm discontinuities and depositional environments on the basis of physical sedimentology alone, ignoring the contributions that the application of ichnology can offer. Integrating the disciplines of ichnology and sedimentology provides the researcher with the ability to characterize sedimentary environments with a higher degree of accuracy than that provided by sedimentology alone. Recent research at the University of Alberta on the Viking Fm in northcentral Alberta and the Bow Island Fm in southern Alberta has taken this approach (MacEachern, 1994; Raychaudhuri, 1994), and this thesis was designed to complement this work.

1.2 Study Area

The thesis study area includes the Mikwan, Fenn West, Fenn Big Valley and Chain gas fields (Fig. 2) which produce from the Viking Fm. These gas fields form elongate deposits on strike with the Gilby-Joffre trend to the northwest. The presence of the Devonian aged Bashaw reef complex, along with economic quantities of gas in the Viking Formation has meant that the area has been extensively drilled, providing an excellent drill core database and good well log control.

The characterization of the facies and discontinuities of the Viking Formation requires adequate subsurface information; specifically, drill core and well log control. The study area was chosen with this in mind and encompasses Townships 32-37 and Ranges 16-24W4, approximately 5034 km^2 in area (Fig. 1).

1.3 Objectives

The objectives of this thesis are two-fold: firstly to establish a high resolution stratigraphic framework for Viking Formation deposits in the study area, and secondly to determine whether they are an extension of deposits in the Joffre field to the northwest. The Viking gas fields in the study area are on strike with the Gilby-Joffre trend. The Gilby field was studied by Raddysh (1988) and the Joffre field by Downing (1986) and Downing and Walker, (1988). More recently, the deposits at Joffre have been re-examined by MacEachern *et al.*, (1995a,b). To answer these questions the record of relative sea level change and the depositional history of the Viking Fm in the study area must be deciphered.

1.4 Methodology and Database

Thirty-seven drill cores were logged in the study area (Fig. 3)using the AppleCORE logging software package. The ichnology, lithology and physical sedimentary structures, along with any possible discontinuities, were examined and described. Drill cores were correlated to their respective geophysical well log suites.

For the next phase of study, 13 working cross-sections were constructed using more than 470 well logs. Cross-sections were correlated using cored wells and their respective well log signatures as a guide. Correlations were checked by "looping" (beginning and ending the cross-section with the same well) the cross-sections, to ensure that correlations remained consistent over the study area. Pertinent well logs were digitized and four representative cross-sections were constructed using the Adobe Illustrator graphics software (Fig. 4).

Using the well logs from the cross-sections as a database, appropriate depths were entered in the Excel spreadsheet program, and subsea and isopach values were calculated. Calculated values were imported into the MCAD Contour mapping program and a variety of structural and isopach maps were produced.

1.5 Regional Stratigraphy

1.5.1 General Stratigraphy

The Viking Formation generally consists of a coarsening upwards succession of marine shales, siltstones and sandstones deposited in the Lower Middle Cretaceous during the Late Albian (Stelck, 1958). Viking Fm sediments pass out of the marine shales of the Joli Fou Fm, onto which it downlaps, and are overlain by the marine shales of the Colorado Gp, recently designated the Westgate Fm (Bloch *et al.*, 1993) (Fig. 5).

1.5.2 Joli Fou Formation

The marine shales of the Joli Fou Fm are distributed throughout the WCSB with the exception of northwestern Alberta. The Joli Fou Formation in Alberta thins from 33m in the north, to 17m in central Alberta (Leckie and Reinson, 1993). In the study area the Joli Fou Fm ranges in thickness from 10 to 15m. Age equivalents of the Joli Fou Formation include the Skull Creek Shale of Montana and North Dakota, the Thermopolis Shale of Wyoming and the Skull Creek Member of Manitoba (Glass, 1990).

Deposits of the Joli Fou Fm are composed of dark gray, non-calcareous marine shale with small quantities of interbedded fine- to medium-grained sandstone and small quantities of nodular phosphorite, bentonite, pelecypod coquinas and concretions of siderite, calcite and pyrite (Leckie *et al.*, 1994)

1.5.3 Viking Formation

The sandstones and shales of the Viking Fm are dominantly marine in origin, and are distributed throughout central to eastern Alberta, as well as southeastern and east-central Saskatchewan (Glass, 1990). The name, Viking sandstone, was first applied informally to the producing unit of the Kinsella field of east-central Alberta by S. E. Slipper (1918) and the Viking Fm was formally named by Dowling *et al.*, (1919).

The thickness of the Viking Formation varies from 40 to 50m through central Alberta and southeastern Saskatchewan, thinning to the north and east (Glass, 1990; Reinson *et al.*, 1994). In southern Alberta and southwestern Saskatchewan the Viking Fm is correlatable to the upper part of the Bow Island Fm (Glaister, 1959). The Viking/Bow Island transition in southern Alberta occurs just north of Township 29 (Raychaudhuri, 1994), where the unit thickens to 65m (Glass, 1990; Reinson *et al.*, 1994). Within the study area, the Viking Fm thickens to 45m in the south and thins basinward to 20m. The Viking Formation is equivalent to the Pelican Fm in northern Alberta and to the Paddy Mbr of the Peace River Fm in northwestern Alberta (Glass, 1990; Leckie and Reinson, 1993). In the United States, the Viking Fm is stratigraphically equivalent to the Newcastle Fm in North Dakota, the J Sandstone in Colorado and the Muddy Sandstone in Montana/Wyoming (Glass, 1990; Reinson *et al.*, 1994).

Lithologically, the Viking Fm is composed of interbedded shales, siltstones, sandstones and conglomerates which have been modified by a wide variety of sedimentary and biogenic structures. The Viking Fm may also contain numerous bentonite deposits, of variable thickness and areal distribution (Amajor and Lerbekmo, 1980).

1.5.4 Westgate Fm

Overlying the Viking Fm are the marine shales of the Lower Colorado Gp, recently raised to formation status and designated the Westgate Fm (Bloch *et al.*, 1993). The Westgate Fm is bound by the Base of Fish Scale Zone (BFS) at its top. Various workers had previously referred to the Westgate Fm as the Shaftesbury Shale (Stelck and Koke, 1987), the Lower Shaftesbury Shale (Stelck, 1958), the Lloydminster Shale (Tizzard and Lerbekmo 1975; Amajor and Lerbekmo, 1980; Hein *et al.*, 1991) and the Colorado Shale (Beaumont,

1984). Some workers have considered the interval between the top of the Viking Fm to the BFS to be part of the Viking alloformation (*cf.* Boreen, 1989; Boreen and Walker, 1991; Hadley, 1992).

The Lower Colorado shales are, for the most part, made up of dark shales and thin, intermittent beds of siltstone and very fine grained sandstone. At the base of the unit are rare, thin to medium beds of coarse grained sandstone and conglomerates.

1.5.5 Biostratigraphy-Megafaunal

Megafossils are rarely found in the subsurface deposits of the Viking Fm, which may be a function of the poor sampling offered by drill core samples. The paucity of megafossils in the Viking Fm precludes their use for biostratigraphic purposes (Stelck, 1958).

1.5.6 Biostratigraphy-Microfaunal

Microfaunal assemblages have proven adequate to define the biostratigraphic zones and subzones in the Joli Fou Fm to BFS interval. However, due to the limited quantities of microfossils in the Viking Fm of central Alberta (Stelck and Koke, 1987) work has focused on the shaly equivalents of the Viking Fm in northeastern British Columbia (Stelck, 1975, 1991; Koke and Stelck, 1985; Stelck and Koke, 1987; Stelck and Leckie, 1990; Caldwell *et al.*, 1993) . The sediments of the Joli Fou and Viking Fm contain the microfossil assemblage of the *Haplophragmoides gigas* Zone (Fig. 6, Stelck and Koke, 1987). The Lower Colorado shales overlying the Viking Fm contain the microfaunal assemblage of the *Miliammina manitobensis* Zone (Stelck, 1958; Stelck and Koke, 1987). The Joli Fou Fm encompasses *Haplophragmoides uniorbis* to *Haplophragmoides gigas phaseolus* Subzones. Further subdivision of the *Haplophragmoides gigas* Zone into seven subzones has demonstrated the presence of unconformities at the base and top of the *H. gigas* Zone (Stelck and Koke, 1987). The Viking Fm is constrained to lie above the *Haplophragmoides gigas phaseolus* Subzone and below the *Miliammina manitobensis* Zone (Fig. 6, Caldwell *et al.*, (1993)). The Viking Fm falls in the mid-Upper Albian Substage of the Early Cretaceous (Koke and Stelck, 1985), which assigns it a time value of between 99 and 100.5 Ma. (Stelck and Koke, 1987).

1.5.7 Chronostratigraphy

Though the Viking and Joli Fou formations contain numerous bentonite beds, little work has been done on dating them. Early work by Folinsbee *et al* (1963) using the technique of Potassium/Argon dating, established an absolute date of 97-99 Ma. for a bentonite bed within the Mowry Shales (*Miliammina manitobensis* Zone) in the Greybull area of Wyoming. The interval from the top of the Viking Fm to BFS is equivalent in age to the Mowry Shale. Further work by Tizzard and Lerbekmo (1975) on age dating of bentonite beds in the Viking established an absolute date of 98-102 Ma.

This date compares favorably with the estimate of 99-100.5 Ma. by Stelck and Koke (1987) and is consistent with an eustatic drop in sea level estimated at 98 Ma. (Haq *et al.*, 1987) that may have led to the deposition of the Viking Fm.

1.6 Structural Setting

The Viking Fm in the study area is located entirely in the subsurface, well to the east of the Foreland Thrust and Fold Belt and is undeformed by any large scale faults or folds. In the study area the Viking Fm is located at subsea depths ranging from -200m to -535m. Regional dip in the study area is a gentle 5.7m/km to the west (Fig. 7)

1.7 Paleogeography and Depositional History

The Viking Fm comprises part of a thick clastic wedge of sediments, which were deposited in the Alberta Foreland Basin from Mid-Jurassic to Late Cretaceous time. The Alberta Foreland Basin formed in response to the accretion of allochthonous terranes to the western margin of the North American Craton (Fig. 8, Cant, 1989; Kauffman and Caldwell, 1993). Accretionary terranes caused tectonic shortening and thickening of the crust, which led to thrust faulting, uplift of the Cordillera and flexural down loading of the crust in the foreland east of the thrust belt, creating a foredeep (Fig. 9, Cant, 1989; Kauffman and Caldwell, 1993; Stott, 1993). The topographic relief of the Foreland Thrust and Fold Belt generated large quantities of eroded sediments, that were shed into the foreland basin, loading the basin

and causing further subsidence (Cant, 1989). All the above elements provided the conditions necessary for the epeiric Western Interior Seaway to persist throughout Cretaceous time, albeit of variable areal extent.

Deposition of sediments in the Foreland Basin during the Cretaceous was controlled by five interrelated factors: 1) global tectono-eustatic and climato-eustatic sea level changes; 2) the tectonic history of the Foreland Thrust and Fold Belt, stable North American craton, foreland basin and Cordillera; 3) watermass dynamics in the epeiric seaway and its relation to the world's oceans; 4) long and short term climatic changes, especially those caused by Milankovitch cycles; 5) and finally the cumulative effect that all these factors had on environmentally sensitive resident biota of the epeiric seaway (Kauffman and Caldwell, 1993).

Deposits of the Albian Joli Fou Fm, Viking Fm and Westgate Fm, record a large scale transgressive-regressive-transgressive cycle. In the Late Middle Albian to Early Late Albian, the Western Interior Seaway connected the Gulf of Mexico and the boreal Arctic Ocean, breaching the Transcontinental Arch (Stelck and Koke, 1987; Kauffman and Caldwell, 1993). In Alberta, this event formed the Joli Fou Sea, evidence for which lies in the presence of fossils of both boreal and Gulfian affinity (Stelck, 1958; Koke and Stelck, 1985; Stelck and Koke, 1987). During this time, fully marine shales were deposited throughout much of northern and central Alberta (Fig. 10, Stott, 1984; Stott, 1993).

During the Late Albian, a fall in relative sea level closed the connection of the Western Interior Seaway to the Gulf of Mexico (Williams and Stelck, 1975; Kauffman and Caldwell, 1993) leading to the deposition of the Viking Fm (Fig. 10). Rising sea levels in the Late Albian meant the return of full marine deposition over much of Alberta (Fig. 10), recorded in the deposits of the Lower Colorado shales.

1.8 Previous Work

Because of the abundance of hydrocarbon deposits, the Viking Fm has long been the subject of commercial and scientific interest. Workers have sought to explain the origin and distribution of the many Viking fields, especially since many are found as elongate, sharp based, coarse grained sandstone bodies that continue along strike for many kilometres (*e.g.*. Judy

Creek, Joarcam and Joffre-Gilby). A depositional model must explain how sharp-based sandstone bodies can be found in an apparent offshore setting, encased in marine shales and siltstones. Though a wide variety of models have been proposed, they all fall into one of two categories: a) models requiring a transport mechanism to move coarse-grained material out to the shelf and form it into offshore bars, and b) models invoking changes in relative sea level that create mobile shorelines.

1.8.1- Offshore, Nearshore, and Barrier Bar Models

Proponents of the offshore transport model have proposed various ways to transport coarse-grained sediments to a shelf setting. Beach (1955) suggested that turbidity currents or tsunamis (Beach, 1956, 1962) were responsible for the transportation of coarse-grained sediments offshore and forming offshore bars. The turbidity current depositional model was also supported by Roessingh (1959), who felt that sedimentary structures (deformation structures), present in cored Viking intervals precluded the possibility that the Viking was deposited in response to fluctuating sea levels.

DeWiel (1956) felt that turbidity currents were not likely to form in a shallow Viking sea and proposed instead that the Viking was deposited during a regressive phase, in shallow water. This view was supported by Glaister (1959) who felt the Viking equivalent in southern Alberta, (the Bow Island Fm) was deposited during repeated regressions within an overall transgression. DeWiel (1956) and Glaister (1959) were the first to propose that changes in sea level were responsible for the deposition and distribution of Viking/Bow Island sandstone bodies; that these were in fact not offshore bars, but were remnant shoreline deposits.

The offshore and nearshore bar interpretation for Viking Fm deposits, and variations upon this theme, remained popular with many workers. Viking Fm deposits were interpreted as nearshore and offshore bars (Stelck, 1958), as shallow bars molded by currents (Gammel, 1955), as offshore bars formed in deepwater by bottom currents (*e.g.*. Joarcam; Hunt, 1954) and as sandstone bars (*e.g.*. Provost; Renaud, 1959). Evans (1970) suggested that linear Viking sandstone bodies in Saskatchewan were deposited by tidal currents in an offshore setting (Evans, 1970). Viking deposits at Suffield were interpreted as barrier bar complexes (Tizzard and Lerbekmo, 1975) while Lerand and Thompson (1976) proposed that Viking deposits at Provost-

Hamilton Lake were deposited as marine bars that accumulated on a submarine shoal. Viking deposits in the Gilby B field were interpreted by Koldijk (1976) to be offshore bars formed by storm-driven currents. Boethling (1977b) suggested that Viking deposition in Alberta had occurred as marine sheet- and bar-sand complexes on a broad sill-like shelf. Deposits of the Viking Fm at Joffre were described by Reinson *et al.*, (1983) as an offshore bar complex, deposited by tidal or storm currents, while Farshori and McKay (1986) suggested that Viking deposits at Giroux Lake were the result of storm currents molding offshore bars. Grujenschi (1983) proposed that storm and tidal currents deposited the elongated sandstone bodies of the Cardium and Viking Fms. The large scale regional studies of Amajor (1978, 1980, 1984) and Amajor and Lerbekmo (1990a, 1990b), while primarily concerned with correlating bentonites within the Viking Fm in central Alberta, did credit tide and storm currents with the formation of offshore and barrier bars.

1.8.2-Relative sea level change models

As previously mentioned, it was DeWiel (1956), and Glaister (1959), who were the first to recognize the importance of sea level fluctuations on the distribution and nature of Viking Fm sediments. It was not until the 1980s, with the advent of sequence stratigraphic principles, that relative sea level changes were proposed as the factor controlling deposition of Viking Fm sandstone bodies. Work has now focused on the recognition of discontinuities within the Viking Fm and the mapping of genetically-related sediments bounded by these discontinuities. Using this approach, sequence stratigraphic and allostratigraphic analyses have been applied to the Viking Fm, and deposits of the Viking Fm can be broken down on the basis of origin, into four types: 1) transgressive shoreface deposits 2) incised valley fill deposits 3) forced regression/lowstand shoreface deposits 4) regional or highstand deposits. This is not to say that at one locality only one type of deposit can be distinguished; in fact it is more likely that complex combinations of the above deposits will be present.

Beaumont (1984) examined the Viking Fm sediments at Joffre and Joarcam and concluded that they represented regressive deposits reworked by a subsequent transgression into linear sandstone bodies. Other workers have interpreted the Joarcam deposits to represent a lowstand/transgressive shoreface complex (Power, 1988), stillstand deposits within an overall

transgression (Pattison, 1991), and as a lowstand/forced regression shoreface (Posamentier and Chamberlain, 1991a; 1991b, Posamentier *et al.*, 1992). Sediments of the Viking Fm at Joffre were interpreted as lowstand shoreface complexes modified by transgression (Downing, 1986; Downing and Walker, 1988).

Recent studies of Viking deposits at Caroline/Garrington have led to its interpretation as a transgressive/regressive complex (Hein *et al.*, 1986, 1991), a regressive/transgressive shoreface complex modified by tidal processes (Leckie, 1986), a stillstand deposit within an overall transgression (Pattison, 1991a), and as a forced regression/transgressive shoreface complex (Davies and Walker, 1993). Viking Formation sediments at Harmatton East and Crossfield have been described as lowstand deposits modified by multiple stillstands within an overall transgression (Hadley, 1992) At Gilby, Raddysh (1988) described the Viking Fm as a lowstand deposit, reworked by a subsequent stillstand, while Pattison (1991a) felt the sediments were deposited during stillstands during an overall transgression. Deposits of the Viking Fm at Chigwell were interpreted by Raychaudhuri (1992) as forming through stillstand deposition within a transgression or forced regression and by Pattison (1991a) as stillstand deposits within an overall transgression. MacEachern (1994) described the Giroux Lake deposits as weakly storm-influenced stillstand parasequences deposited during transgression, and Kaybob deposits as a weakly storm-influenced forced regression shoreface.

The final category of Viking Fm deposits are the incised valley fills. The discovery and recognition of incised valley fill deposits within the Viking Fm has led to a great body of work. Incised valleys in the Viking Fm are generally filled with estuarine sediments. From a sequence stratigraphic perspective, they are cut during lowstand with only local preservation of lowstand deposits. The bulk of the incised valley fill is deposited during the subsequent transgression. Incised valley fill deposits have been described at Crystal (Leckie and Reinson, 1993; MacEachern, 1994; Pattison, 1991a, 1991b, 1992; Pattison and Walker, 1994, Pemberton *et al.*, 1992), Willesden Green (Boreen and Walker, 1991; MacEachern, 1994), Cyn-Pem (Pattison, 1991a; MacEachern, 1994), Sundance (Pattison, 1991a,1992; MacEachern, 1994), Fox Creek (MacEachern, 1994) and Edson (Pattison, 1991a: MacEachern, 1994). Perhaps one of the most challenging problems yet to be addressed involves

the reconciliation of the various interpretations and terminology's into a coherent sequence stratigraphic framework.

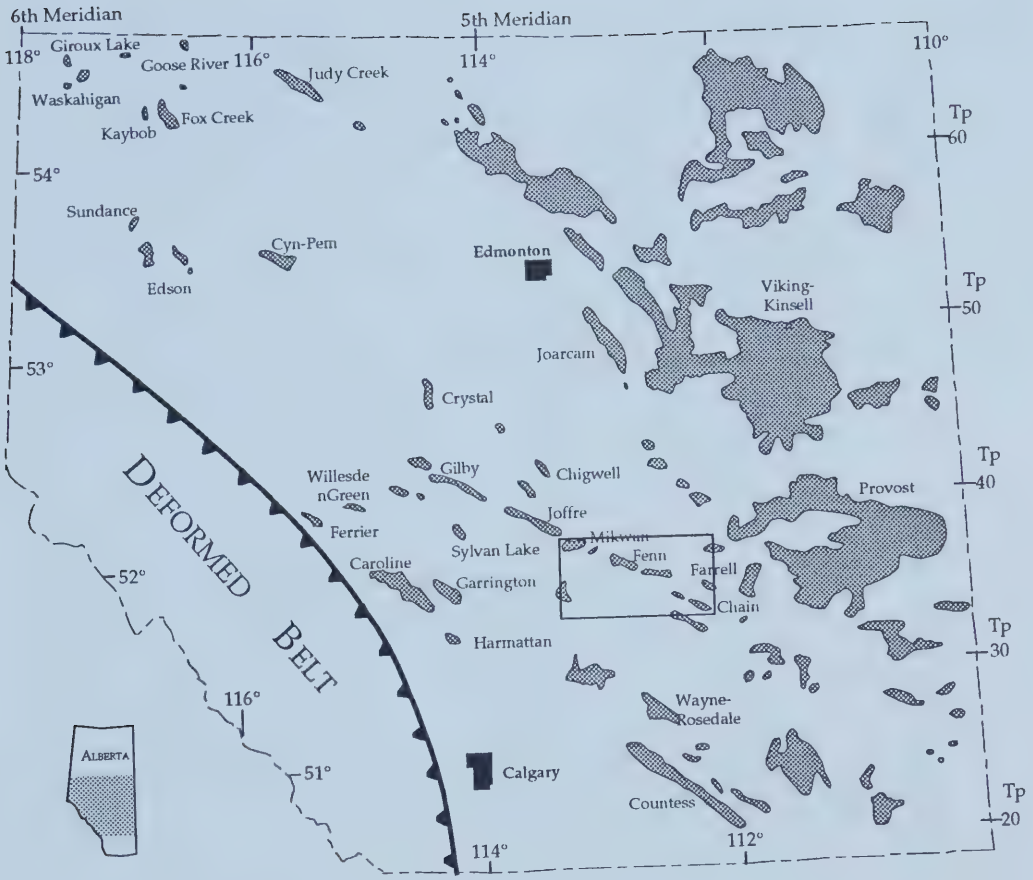


Figure 1- Location of Viking oil and gas fields in south central and central Alberta. Study area is outlined by box (modified after MacEachern, 1994).

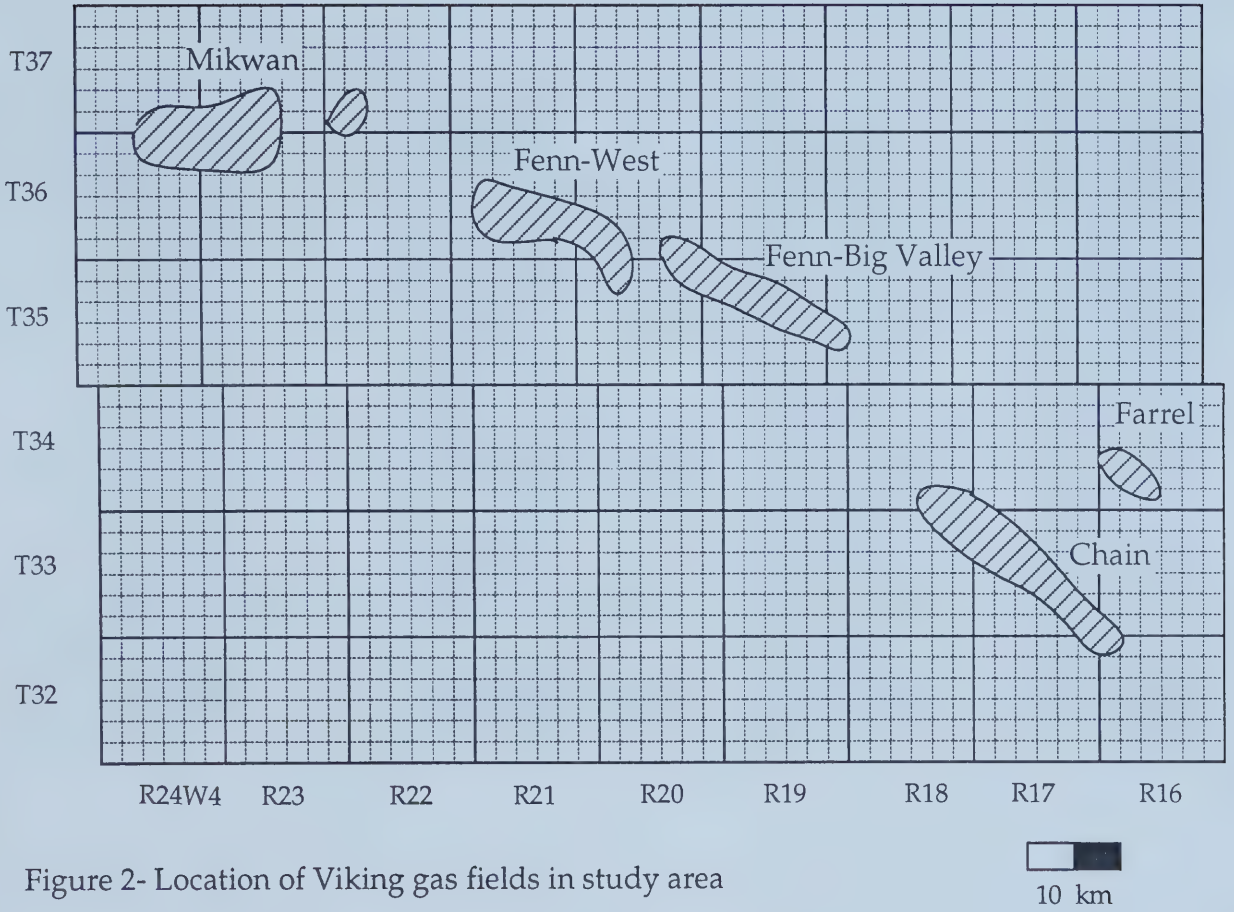


Figure 2- Location of Viking gas fields in study area

Cores logged at Mikwan, Fenn West, Fenn Big Valley and Chain Fields		
Locations	Kb	Core Interval
10-3-32-17W4	849m	1071-1089m
10-7-32-20W4	849m	1197-1210m
11-6-33-20W4	826m	1190-1199m
6-12-34-17W4	827m	1033-1073m
12-8-34-18W4	855m	1130-1148m
3-17-34-18W4	846m	1117-1135m
7-18-34-18W4	861m	1140-1152m
14-18-34-18W4	859m	1131-1148m
6-20-34-18W4	835m	1098-1110m
11-2-34-20W4	860m	1206-1225m
11-13-34-20W4	889m	1220-1239m
14-27-34-20W4	847m	1186-1194m
2-33-34-20W4	840m	1178-1196m
10-4-34-24W4	928m	1478-1493m
2-30-35-19W4	851m	1168-1176m
8-2-35-20W4	852m	1186-1203m
10-35-35-20W4	864m	1200-1214m
16-19-36-21W4	870m	1291-1306m
4-32-36-21W4	911m	1332-1342m
8-1-36-22W4	847m	1275-1293m
10-15-36-22W4	895m	1349-1366m
3-31-36-22W4	915m	1391-1406m
7-20-36-23W4	943m	1458-1478m
7-29-36-23W4	936m	1450-1468m
14-36-36-23W4	919m	1402-1420m
10-25-36-24W4	930m	1455-1485m
10-2-37-23W4	899m	1383-1401m
10-8-37-23W4	869m	1377-1395m
10-17-37-23W4	881m	1390-1400m
3-18-37-23W4	859m	1369-1383m
7-20-37-23W4	873m	1366-1400m
10-30-37-23W4	865m	1358-1373m
7-1-37-24W4	883m	1402-1417m
7-13-37-24W4	863m	1371-1385m
10-16-37-24W4	901m	1437-1450m
11-24-37-24W4	667m	1361-1379m
12-32-37-24W4	870m	1420-1424m

Figure 3-List of drill cores and intervals logged in study area

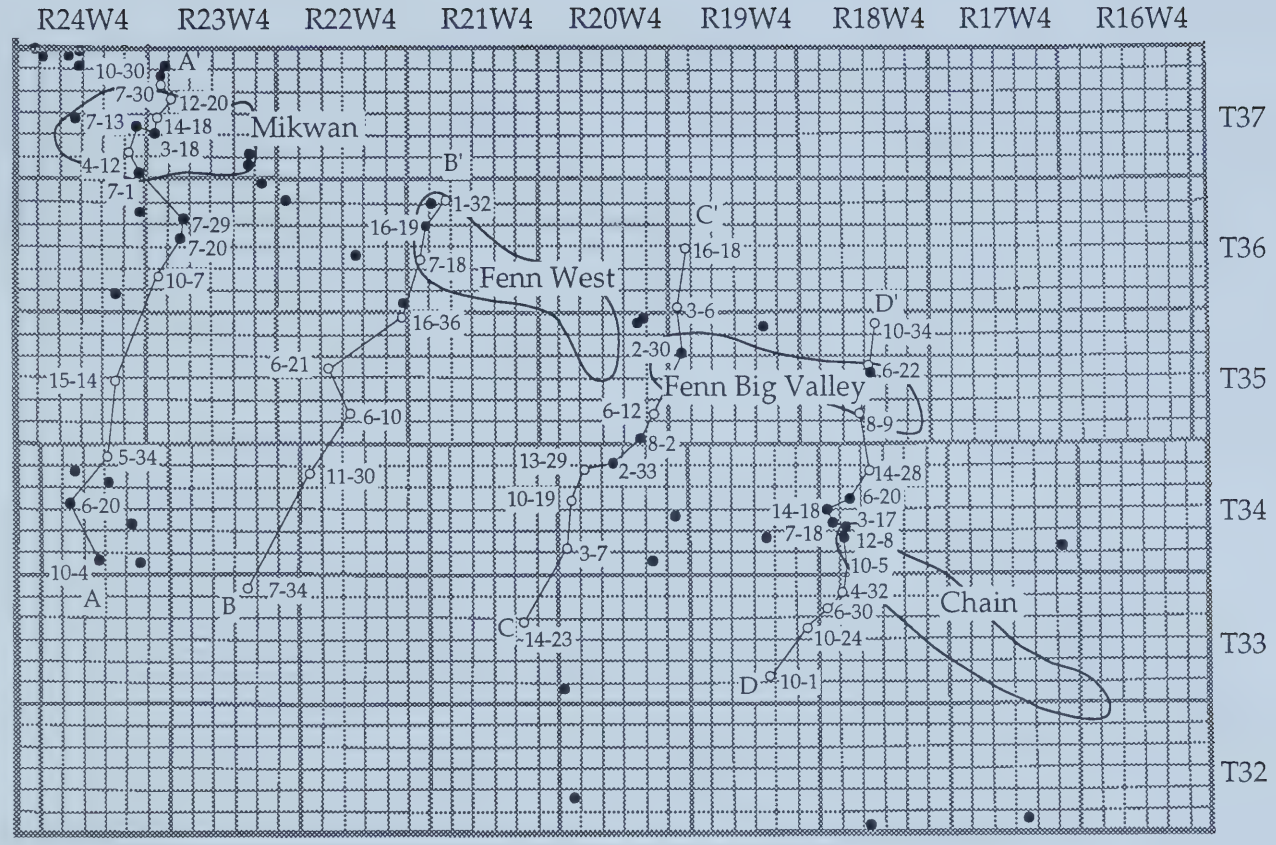


Figure 4-Cross-section and core locations in study area

10 km

Legend

Cored Wells •

Well logs only ○

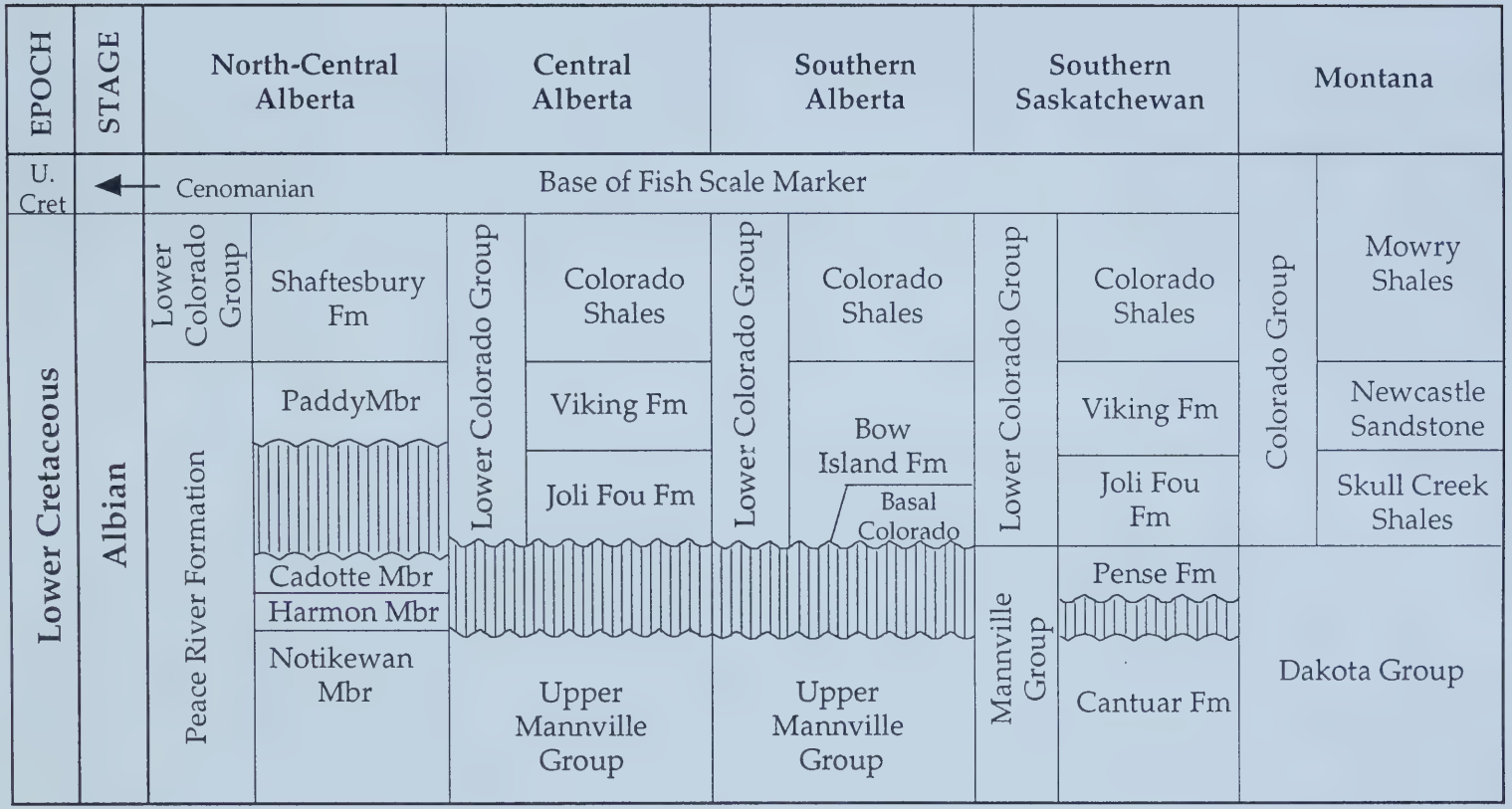


Figure 5-Stratigraphic correlation chart for the Viking Formation and equivalents in Alberta, Saskatchewan and Montana (modified after MacEachern, 1994).

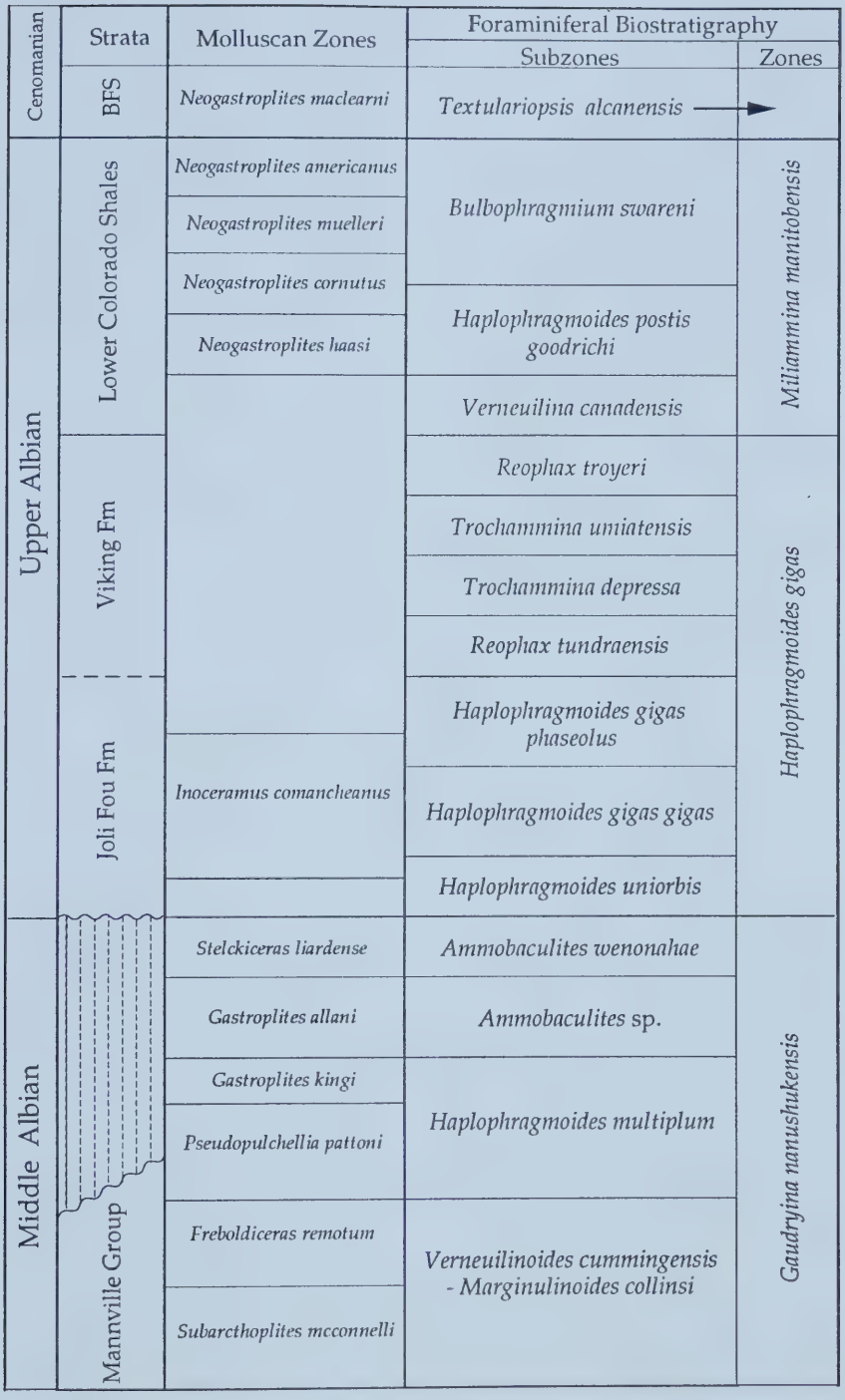


Figure 6-Foraminiferal and molluscan biostratigraphy of the Viking Fm in central Alberta (modified from MacEachern, 1994).

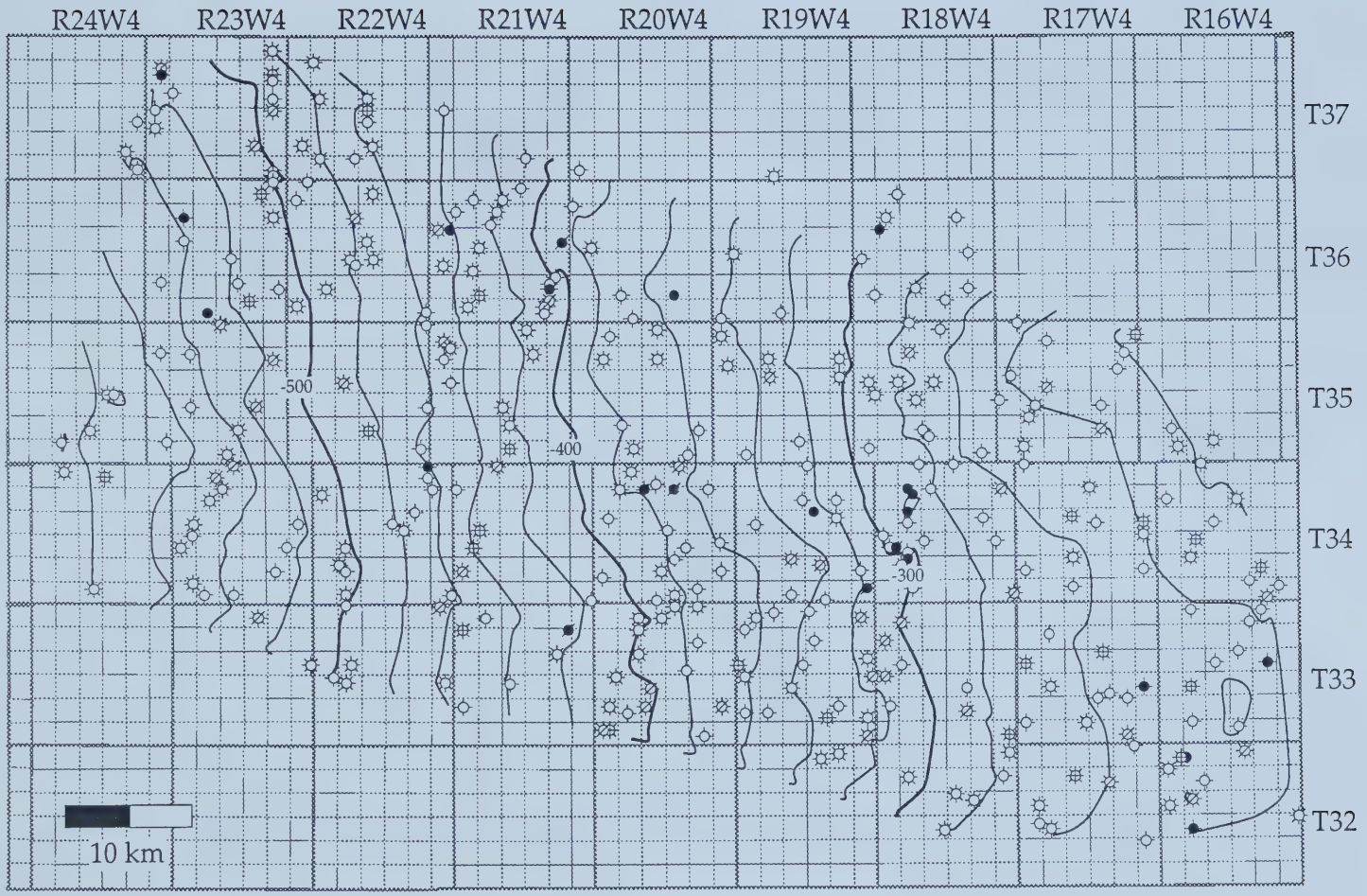


Figure 7- Structure on a bentonite marker within the regional Viking Fm in the study area.
Contour Interval is 20m

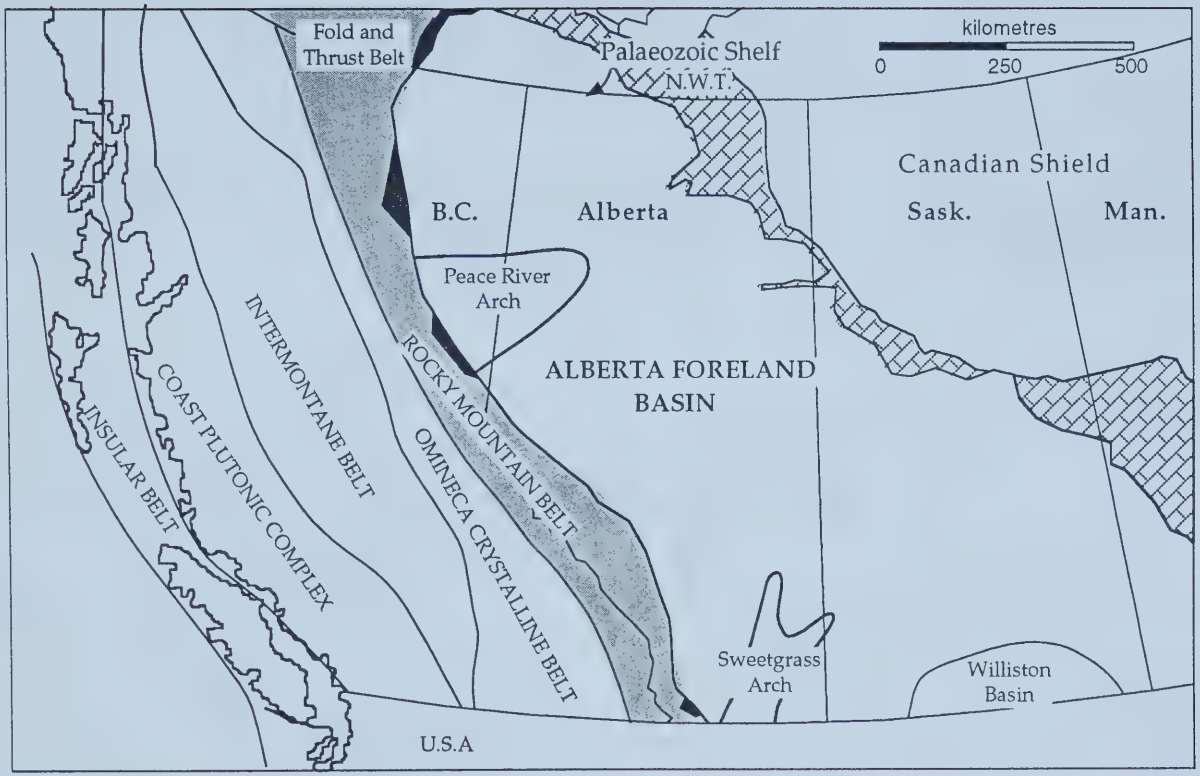


Figure 8-Tectonic belts of the Canadian Cordillera and elements of the Western Canadian Sedimentary Basin (modified after Cant, 1989; McMechan and Thompson, 1993)

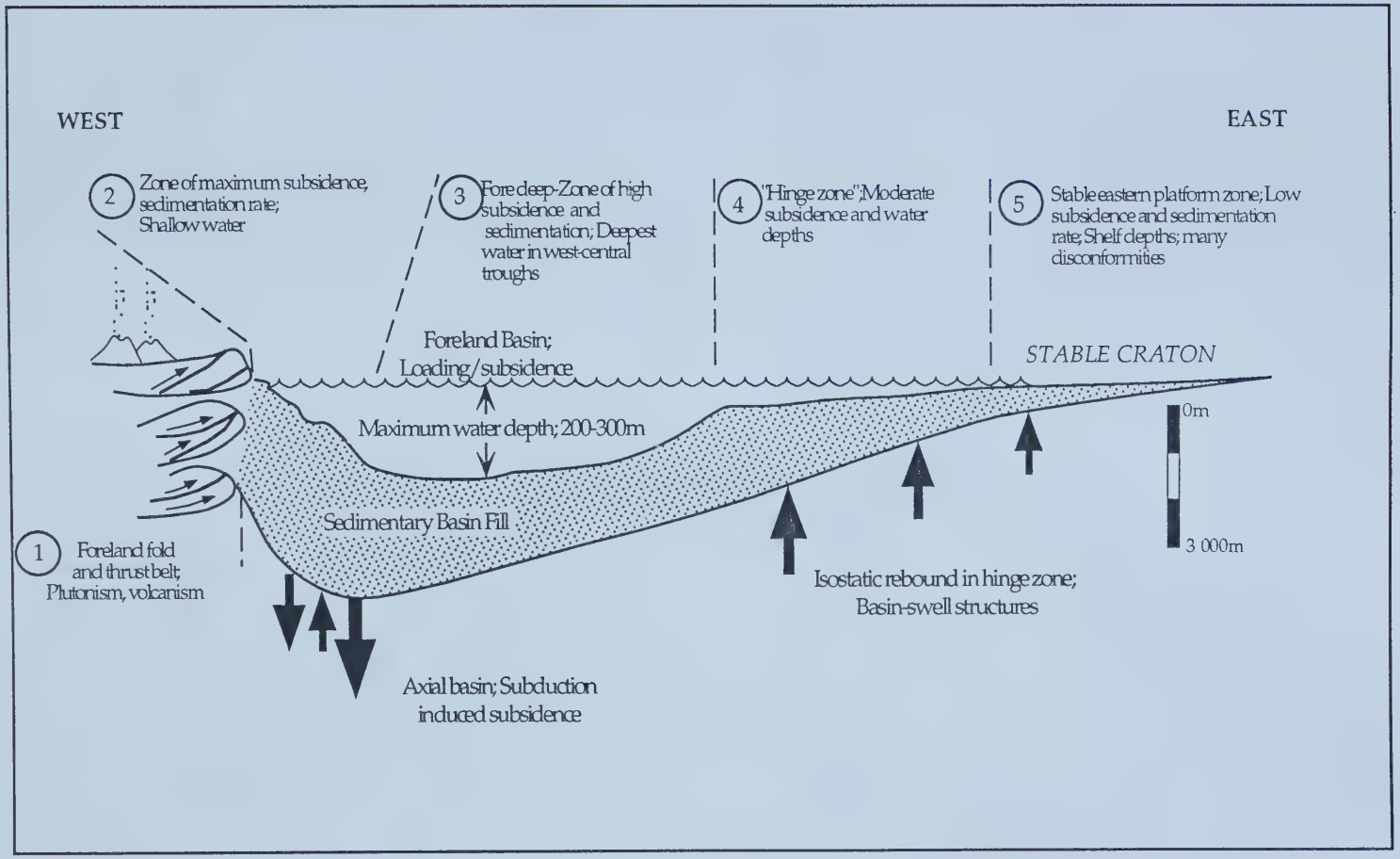

WEST
EAST
2 Zone of maximum subsidence, sedimentation rate; Shallow water
3 Fore deep-Zone of high subsidence and sedimentation; Deepest water in west-central troughs
4 "Hinge zone"; Moderate subsidence and water depths
5 Stable eastern platform zone; Low subsidence and sedimentation rate; Shelf depths; many disconformities
Foreland Basin; Loading/subsidence
STABLE CRATON
Maximum water depth; 200-300m
0m
3 000m
Sedimentary Basin Fill
1 Foreland fold and thrust belt; Plutonism, volcanism
Isostatic rebound in hinge zone; Basin-swell structures
Axial basin; Subduction induced subsidence

Figure 9- Schematic diagram of the elements of the Alberta Foreland Basin (modified after Leckie (1989)

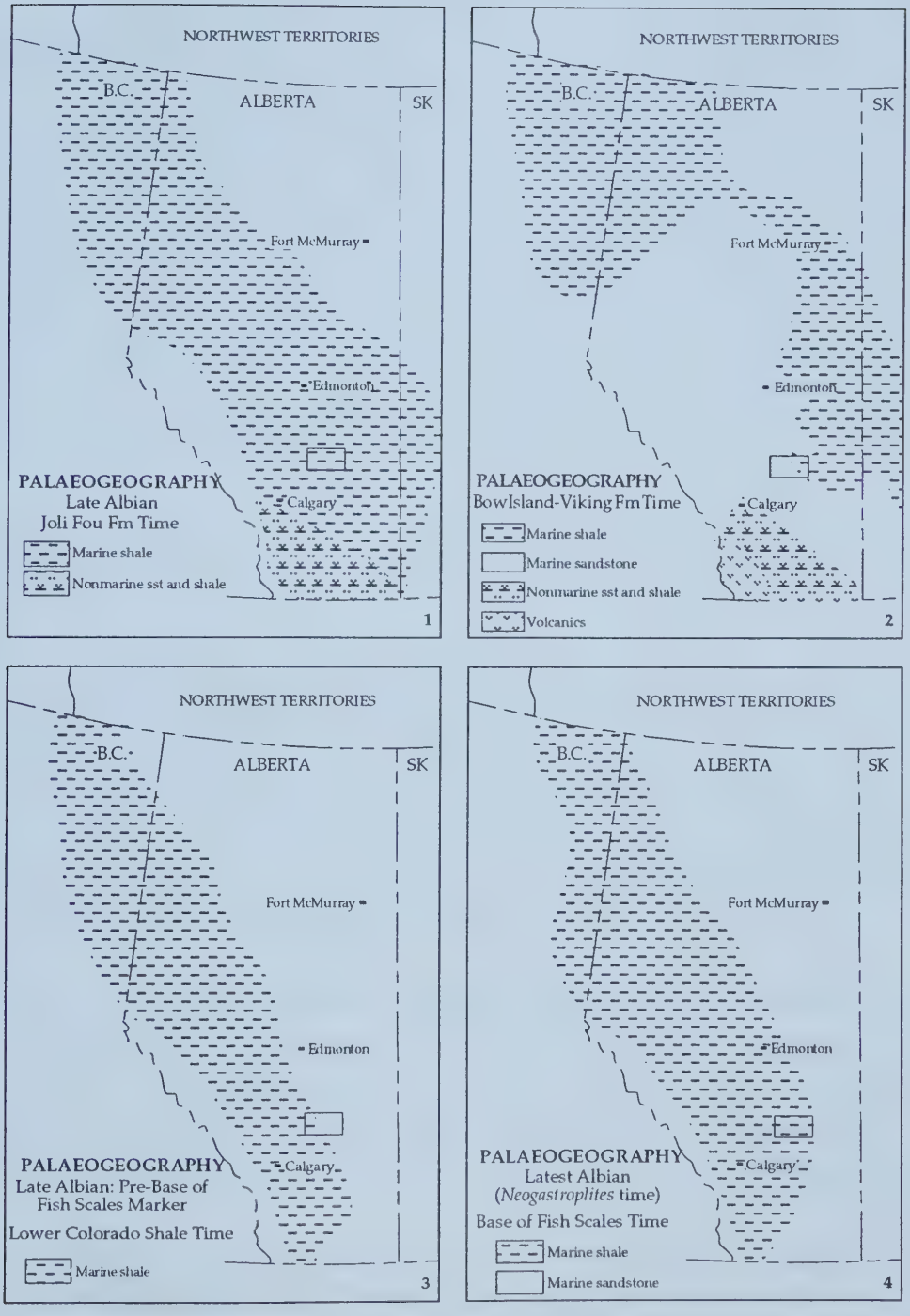


Figure 10-Palaeogeography during the Upper Albian Substage. Study area outlined by rectangle (modified from Stott, 1984).

CHAPTER 2: FACIES DESCRIPTIONS AND INTERPRETATIONS

2.1 Introduction

Careful logging of all pertinent core in the study area has led to the subdivision of the Viking Fm deposits into 13 facies. Facies are defined on the basis of lithology, sedimentary structures and ichnology. This chapter describes the sedimentology and ichnology of each facies and proposes a possible environment of deposition consistent with its description. Facies in the study area are very similar to those described by Downing (1986) from the Joffre field to the northwest. A brief comparison of the facies nomenclature used in this study and that of Downing (1986) is offered in Table 1. Table 2 summarizes the relative abundance of ichnogenera in each facies.

2.2 Facies 1: Dark gray to black, thoroughly bioturbated, silty and sandy mudstone

Sedimentology: Facies 1 is thoroughly bioturbated, with the exception of rare, intermittent, thin (2-4 cm), sharp based, fining upwards beds of very fine-grained gray sandstone. These sandstone beds are intensely bioturbated but may locally display remnant wavy parallel laminations. Bioturbation in most cases has obliterated the beds, leaving only pods or lenses of very fine-grained sandstone and siltstone (Fig. 11a,d). Facies 1 is stratigraphically the lowermost facies found in drill core in the study area.

Ichnology: Since Facies 1 has been so thoroughly bioturbated, it is difficult to distinguish individual traces (Fig. 11). Ichnogenera present include abundant *Teichichnus, Helminthopsis, Planolites,* along with *Terebellina, Chondrites, Zoophycos and Rosselia.* Associated with the beds of very fine-grained sandstone are *Diplocraterion, Asterosoma, Siphonichnus* and *Palaeophycus.*

Interpretation: The lack of sedimentary structures, the very fine grain size and thorough bioturbation of Facies 1 is consistent with deposition in a lower offshore, fully marine setting, below fairweather wave base and at the lower limit of the stormweather wave base (Pemberton *et al.,* 1992b; MacEachern, 1994). The predominance of deposit feeding trace makers with a significant

component of grazing structures is typical of the distal *Cruziana* ichnofacies (Fig. 12) which also supports a lower offshore setting (MacEachern and Pemberton, 1992; Pemberton *et al.*, 1992a). The thin, sharp based, normally graded sandstone beds found in Facies 1, were deposited by storm events.

2.3 Facies 2: Pale gray, thoroughly bioturbated, shaly siltstone and sandstone.

Sedimentology: Facies 2 consists of muddy, thoroughly churned, pale gray siltstone and fine-grained sandstone. Rare, sharp-based, fining upwards, wavy parallel laminated, fine-grained sandstone beds, (2 to 5cm thick) are distributed throughout Facies 2. Tops of sandstone beds are bioturbated. Most sandstone beds have been "shredded" by bioturbation and are discontinuous on the scale of core (Fig. 13).

Ichnology: A diverse and robust trace assemblage is present in Facies 2 (Fig. 13). Traces such as *Rosselia, Terebellina, Palaeophycus, Anconichnus* and *Teichichnus* are prevalent throughout Facies 2. Less abundant are the *Schaubcylindrichnus, Ophiomorpha, Asterosoma, Subphyllochorda, Planolites, Chondrites* (largely restricted to organic mud partings), *Siphonichnus, Planolites, Arenicolites* and *Helminthopsis* . Burrowing is uniformly distributed.

Interpretation: Facies 2 is very similar to Facies 1 and was deposited under very similar conditions, but in a slightly more proximal setting consistent with the increased sandstone and siltstone content. The increased variety of trace fossils visible in Facies 2 may be due to the greater contrast provided by the higher quantities of sandstone and siltstone present. The homogenized, thoroughly churned texture, and lack of physical sedimentary structures in Facies 2, along with the sandstone and siltstone content, indicates that Facies 2 was deposited in a fully marine proximal upper offshore to distal lower shoreface setting. The rare, fining upwards, sharp based, thin sandstone beds are characteristic of storm deposits suggesting that Facies 2 was deposited below fairweather wave base but within storm weather wave base. The diverse and abundant assemblage of trace fossils belongs to the *Cruziana* ichnofacies (Fig. 12)

2.4 Facies 3: Pale gray, shaly sandstone and ripple laminated sandstone.

Sedimentology: Facies 3 consists of lower to upper medium-grained, moderately-sorted, shaly sandstone and lithic sandstone (Fig. 13). The facies coarsens and sands upwards as Facies 3 gradationally changes from a well-bioturbated muddy sandstone to a moderately to weakly bioturbated, hummocky cross-stratified, thickly bedded (20-50 cm) sandstone. The basal portion of Facies 3 is well churned by bioturbation with intermittent, sharp-based, thin (3 to 6 cm), fining upwards, parallel laminated, lower medium-grained sandstone beds. The tops of the HCS beds in the upper portion of Facies 3 are oscillation ripple laminated and are defined by shale fragments.

Ichnology: Traces in the lower portion of the facies include *Palaeophycus* (abundant), *Schaubcylindrichnus, Ophiomorpha, Teichichnus, Planolites, Anconichnus, Diplocraterion* (in sandstone beds), and *Terebellina* (Fig. 14). *Ophiomorpha* constitutes the only trace fossil encountered in the upper oscillation ripple laminated portion of the facies.

Interpretation: Facies 3 is interpreted to be representative of a coarsening and sanding upwards, distal lower shoreface to middle shoreface succession. The deposition of sharp-based, fining upwards, hummocky cross-stratified sandstone beds can be attributed to storm deposition, while the interbedded, muddy, bioturbated sandstone reflects deposition during fairweather conditions, above the fairweather wave base. The hummocky cross-stratification in the upper portion of Facies 3 reflects greater storm influence, associated with shallowing during progradation. Oscillation ripple laminae present at the tops of these beds correspond to post-storm waning energy conditions (Fig. 14d). The trace fossil assemblage, along with the sedimentary structures, places Facies 3 in the proximal to distal *Cruziana* ichnofacies (Fig. 12).

2.5 Facies 4: Pebbly , black, burrowed, interbedded shale and fine- to medium-grained sandstone

Sedimentology: Facies 4 consists of interbedded shale and fine- to medium-grained sandstone. Granule to pebble sized, subrounded, chert clasts are

dispersed throughout the facies, decreasing in both quantity and size towards the top of Facies 4 (Fig. 15). Black shale is interbedded with thin (< 5cm) beds of massive to planar laminated upper fine-grained sandstone. Bioturbation in Facies 4 has obliterated most sandstone beds, leaving only pods and lenses of sandstone that are discontinuous on the scale of the core. Burrowing intensity and sand content increases upwards in Facies 4.

Ichnology: Due to the high shale content of Facies 4, biogenic structures are hard to discern and are only visible where increased sandstone content helps to define burrow structures. The only traces observed in Facies 4 were *Planolites, Anconichnus, Teichichnus, Thalassinoides, Palaeophycus* and *Arenicolites* (Fig. 15).

Interpretation: The high shale content along with the thin interbeds of sandstone supports deposition below the fairweather wave base, punctuated by storms, similar to Facies 1. Planar laminated sharp-based, sandstone beds were deposited by storm events in an upper offshore setting. The trace fossil suite in Facies 4 may be placed in the *Cruziana* ichnofacies (Fig. 12). The granules and pebbles of chert in Facies 4 may be the distal equivalents of ravinement processes, and were transported to the offshore by storms.

2.6 Facies 5: Pebbly, pale gray, well-burrowed shaly sandstone

Sedimentology: Facies 5 is characterized by sanding upwards, pale gray, moderately-sorted, fine-grained to medium-grained, coarsening upwards shaly sandstone with dispersed granules and pebbles of chert throughout (Fig. 16). Chert clasts are sub-angular to sub-rounded and decrease in quantity upwards. Trace amounts of glauconite impart a greenish hue to the facies. Glauconite content increases upwards and Facies 5 is commonly sideritized at the top. The top of facies 5 may exhibit preserved beds of trough cross-stratified sandstone on the scale of 3-10 cm in thickness, while the rest of the unit has been thoroughly churned by bioturbation.

Ichnology: Facies 5 is well burrowed and displays a diverse and abundant trace fossil assemblage typical of the proximal *Cruziana* ichnofacies (Fig. 12). Traces present in Facies 5 include abundant *Zoophycos, Rosselia,*

Palaeophycus, *Subphyllochorda*, *Anconichnus* and *Planolites* along with less common *Thalassinoides*, *Skolithos*, *Arenicolites*, *Terebellina*, *Asterosoma* and *Ophiomorpha* (Fig. 16).

Interpretation: The dominant bioturbate texture of Facies 5, along with its diverse and robust trace assemblage, indicates that deposition occurred in fully marine conditions above fairweather wave base in a lower shoreface setting. The presence of trough cross-bedded sandstone in the upper portion of Facies 5 are interpreted to represent storm deposition in a lower shoreface setting. Chert clasts may have been cannibalized from underlying deposits or may reflect ongoing ravinement in a shallower water setting and transported seaward by storm-generated currents.

2.7 Facies 6: Poorly-sorted, pebbly, coarse-grained muddy sandstone, sandstone and conglomerate

Sedimentology: Facies 6 is highly variable and composed of either poorly sorted, pebbly, cherty sandstone, matrix-supported conglomerates, clast-supported conglomerates, or combinations of the above. Subrounded to subangular chert pebbles are distributed throughout the facies and are commonly concentrated into pods and lenses (Fig. 17). A general lack of sedimentary structures is common with the exception of matrix-supported conglomerates, which have faint indications of cross-bedding (trough?) in some drill cores. The matrix is composed of mudstone and upper fine-grained to coarse-grained sandstone. Polymict clasts are subrounded to well rounded and 1.5 to 2.5 cm in size. Facies 6 is sharp based and may locally display inverse or normal grading.

Ichnology: The cherty sandstone and muddy sandstone of Facies 6 have a bioturbate texture but it is difficult to distinguish individual ichnogenera. Identified trace fossils include *Teichichnus*, *Thalassinoides*, *Skolithos*, *Diplocraterion*, *Ophiomorpha*, and *Palaeophycus* representing a *Skolithos* ichnofacies (Fig. 17). The conglomerates are rarely burrowed.

Interpretation: Deposition of Facies 6 has likely occurred in a lower shoreface or shallower setting, demonstrated by the presence of pebbly muddy

sandstone and cross-bedded sandstone and conglomerates. Deposition was likely rapid, as indicated by poor sorting. Facies 6 may locally represent the distal expression of a conglomeratic, high energy shoreface or constitute a remnant lag deposit on a discontinuity surface.

2.8 Facies 7: Rarely to moderately burrowed shale, interbedded with rippled sandstone

Sedimentology: Facies 7 is dominated by black shale (60-80%) with intermittent, thin (1-3cm thick), sharp-based beds of ripple laminated, fine-grained sandstone (Fig. 18). Dispersed granules and pebbles of chert are present throughout the facies and are commonly concentrated into lenses. Thin beds of fine grained sandstone make up 30% of Facies 7 and display oscillation and combined flow ripple laminations. Rare synaeresis cracks are also present in Facies 7 (Fig. 18).

Ichnology: Irrespective of lithology, the burrowing intensity in Facies 7 may range from rare in some intervals, to moderate in others. Burrowed portions are dominated by a low diversity assemblage of diminutive *Teichichnus, Planolites, Palaeophycus,* with rare *Terebellina* (Fig. 18), attributable to an impoverished *Cruziana* ichnofacies.

Interpretation: The fine grained nature of Facies 7 suggests deposition by suspension in a low energy setting. Thin beds of fine-grained sandstone are the expression of distal storm deposits. The presence of synaeresis cracks and the intervals of little or no burrowing indicate that this was a stressed environment, likely with variable salinities. This indicates that Facies 7 was not deposited in a fully marine setting and was likely deposited in a restricted marginal marine setting, such as a sheltered brackish bay.

2.9 Facies 8: Interbedded glauconitic muddy sandstone, trough cross-bedded sandstone and sideritized mudstone

Sedimentology: Facies 8 consists of 10-50% glauconitic muddy sandstone, 10-40% glauconitic trough cross-bedded sandstone and less than 15% of sideritized mudstone (Fig. 19). The muddy sandstone has a churned texture,

is commonly sideritized and composed of fine-grained to medium-grained, well-sorted cherty, quartz sandstone with abundant glauconite dispersed throughout. The muddy sandstones range from 5-20 cm in thickness and are interbedded with sideritized mudstones and trough cross-bedded glauconitic sandstones. The trough cross-bedded glauconitic sandstones sharply overlie either muddy sandstones or sideritized mudstones, vary from 6-20 cm in thickness and are composed of fine-grained to medium-grained black chert and quartz sand with abundant glauconite. Foresets are defined by glauconitic and black chert grains, and dip at 10-15°(Fig. 19b). Well-rounded, elongate clasts of sideritized mudstones, ripped up from the underlying mudstone beds, and incorporated into the foresets of trough cross bedded sandstones (Fig. 19c) are visible in some intervals. Capping many of the trough cross-bedded sandstones in Facies 8 are thin (3-5cm thick) beds of thoroughly sideritized mudstones (Fig. 19a).

Ichnology: Bioturbation in Facies 8 is restricted to the muddy sandstone. Sideritization of the muddy sandstone has made it difficult to distinguish individual ichnogenera. *Palaeophycus, Ophiomorpha* and *Planolites*. are visible (Fig. 19d). If any traces were present in the mudstones they have been overprinted and obscured by the siderization process. *Arenicolites, Skolithos,* and *Diplocraterion* may be present in some trough cross-bedded sandstone beds of Facies 8. Some sideritized mudstone beds may have *Thalassinoides, Skolithos* and *Arenicolites* burrows infilled with sand of the overlying trough cross-bedded sandstone.

Interpretation: Deposition of sediments in Facies 8 occurred under varying energy levels, alternating between rapid and slow deposition. Trough cross-bedded sandstone was deposited by strong, apparently unidirectional currents while the interbeds of sideritized mudstone and bioturbated muddy sandstone was deposited in a low energy setting. Trace fossils indicate that deposition occurred in a marine or possibly restricted marginal marine setting. The deposition of trough cross-bedded sandstone, muddy sandstone and thin mudstone beds suggest an environment where episodic currents are generated, followed by periods of low energy. These features are indicative of deposition in a tidal environment.

2.10 Facies 9: Interbedded cross-bedded sandstone, bioturbated muddy sandstone and mudstone

Sedimentology: Facies 9 is composed of 30-50% cross-bedded sandstone, 20-40% muddy sandstone and less than 10% mudstone. Facies 9 is very similar to Facies 8 except for two differences: 1) only trace amounts of glauconite are present, and 2) sideritization of mudstones and muddy sandstone is not as prevalent as it is in facies 8. Cross-bedded (trough?) sandstones are composed of lower medium- to upper medium-grained quartz sandstone with disseminated grains of black chert (Fig. 20). Beds have sharp bases and are 10-20 cm thick. Some cross-beds contain angular rip-up clasts incorporated from the underlying mudstone beds. Cross-bedded sandstones sharply overlie beds of 10-30cm thick, bioturbated muddy sandstone (Fig. 20) or thin (1-3cm thick) beds of mudstone and sideritized mudstone (Fig. 20). Both cross-bedded sandstones and muddy sandstones have a "salt and pepper" appearance, resulting from the black chert grains dispersed throughout facies.

Ichnology: No trace fossils were observed in the cross-bedded sandstone and mudstones of Facies 9. The muddy sandstones were burrowed with abundant *Palaeophycus*, *Ophiomorpha* and *Thalassinoides*.

Interpretation: Facies 9 was deposited in an environment very similar to that of Facies 8. The only differences are a change in sediment source and a more restricted environment, as evidenced by the lower diversity trace assemblage.

2.11 Facies 10: Interbedded cherty sandstone, muddy sandstone and mudstone

Sedimentology: Facies 10 is composed of 40-50% cherty cross-bedded sandstone, 40-50% muddy sandstone and less than 10% mudstone. Cross-bedded sandstone consists of moderately-sorted, upper fine-grained to lower medium-grained chert grains (Fig. 21). Cross-beds in the sandstones are poorly defined, but where visible, have steeply dipping foresets (10-15°), consistent with trough cross-bedding. Chert pebbles are dispersed throughout the cross-bedded portion of Facies 10 and typically define individual foresets of cross-beds. Large (2-5 cm long), subrounded to angular rip-up clasts of underlying mudstone are commonly found at the base of cross-bedded

sandstone. Cross-beds sharply overlie the mudstone and muddy sandstone elements of Facies 10. Muddy sandstone intervals are well bioturbated and 10-30 cm thick. Mudstone beds are thin (0.2 to 3 cm thick) and, unlike Facies 8 and 9 are not sideritized.

Ichnology: Muddy sandstones are well burrowed with *Teichichnus, Asterosoma, Palaeophycus* and *Diplocraterion* (Fig. 21). The tops of cross-bedded sandstone are commonly burrowed with *Thalassinoides, Palaeophycus* and *Ophiomorpha*. Mudstone beds may have *Thalassinoides* burrows infilled with sand from overlying cross-bedded and/or muddy sandstones.

Interpretation: The depositional environment for Facies 10 is very similar to that of facies 8 and 9. Higher energy conditions may be implied by the presence of pebbles, and steeply dipping foresets in the cross-bedded sandstone.

2.12 Facies 11: Interbedded buff-colored silty sandstone, bioturbated muddy sandstone and black mudstone

Sedimentology: Facies 11 is composed of 30-40% silty sandstone, 30-40% shale, and 30-40% muddy sandstone (Fig. 22). The very fine-grained, silty, sharp-based, sandstone beds are buff in color and vary from 1 to 6 cm in thickness. Sedimentary structures include wavy parallel laminations, current ripple laminations and combined flow ripple laminations. The tops of the beds may be burrowed. Stringers and lenses of medium-grained sandstone are found distributed throughout this facies. The buff-colored sandstone beds sit sharply on black mudstone beds, which, with the exception of rare siltstone stringers, are apparently structureless. Interbedded with the above elements of Facies 11 are thick, (10-30cm) sharp-based beds of muddy, well-bioturbated medium-grained sandstone. These beds are poorly sorted, with abundant granules of black chert and rare, but uniformly distributed large, angular coal clasts. All sedimentary structures in the muddy sandstones have been destroyed by pervasive bioturbation.

Ichnology: The intensity of burrowing in Facies 11 is highly variable. The buff colored sandstone may be moderately to well burrowed in some intervals, while other intervals may not be burrowed at all. The interbeds of black mudstone display little or no burrowing. When burrowing does occur in the buff colored sandstone, a restricted assemblage of diminutive traces, are commonly represented by the ichnogenera *Diplocraterion, Palaeophycus, Planolites, Ophiomorpha, Skolithos* and *Cylindrichnus*. Bioturbation in the muddy sandstone is so thorough that individual ichnogenera are difficult to pick out. The trace fossils *Diplocraterion, Palaeophycus, Rosselia, Terebellina* and *Teichichnus* are, however locally visible. The trace fossil suite reflects a fairly diverse *Cruziana* ichnofacies.

Interpretation: Sedimentary structures in the sandstone, together with the interbedded shales indicate that Facies 11 was deposited below fairweather wave base but within storm weather wave base, probably in an upper offshore setting. The abrupt changes in burrowing intensity in Facies 11 indicate that environmental stresses were acting periodically throughout its deposition. Decreases in the oxygen or food supply, fluctuations in salinity, changes in depositional rates, or a combination of these factors could have acted as a stress that limited bioturbation. Storms may have temporarily increased the supply of food or oxygen in Facies 11, which would have led to an increase in bioturbation until normal fairweather conditions returned.

2.13 Facies 12: Hummocky cross-stratified sandstone, interbedded with muddy sandstone

Sedimentology: Facies 12 is a sanding-upwards succession of interbedded, thin (2-5 cm) wavy parallel laminated sandstone beds and muddy sandstone beds, grading into thick, (5-30 cm) beds of hummocky cross-stratified sandstone interbedded with black mudstones at the top (Fig. 23). Sandstones throughout Facies 12 are well sorted, very fine-grained and buff in color. All sandstone beds are sharp based, with burrowed tops and may incorporate mudstone rip-up clasts from the underlying mudstone beds. Bioturbation in the lower portion of this facies has "shredded" some of the beds. Sandy mudstones are well bioturbated and do not display any preserved sedimentary structures.

Ichnology: Facies 12 displays a diverse and robust trace fossil assemblage. In muddy sandstones the trace fossils *Chondrites, Palaeophycus, Zoophycos, Rhizocorallium, Diplocraterion, Teichichnus, Ophiomorpha, Cylindrichnus, Asterosoma, Thalassinoides, Anconichnus, Subphyllochorda* and *Siphonichnus* are represented, corresponding to a fully marine proximal *Cruziana* ichnofacies. Burrowing intensity and diversity decreases in the sandstone beds, and only the traces *Rosselia, Siphonichnus* and *Ophiomorpha* are observed. The trace fossil suite is consistent with a proximal *Cruziana* to distal *Skolithos* ichnofacies, but the diminished diversity highlights environmental stress on the infaunal organisms.

Interpretation: Facies 12 is representative of a storm dominated lower shoreface succession. Storm activity deposited the wavy parallel and hummocky cross-stratified sandstone beds while fairweather conditions are represented by the interbeds of well-bioturbated muddy sandstone. A return to fairweather conditions allowed the colonization of the tops of storm beds by trace-making organisms.

2.14 Facies 13: Dark black mudstone

Sedimentology: Facies 13 consists of rubbly, dark black, massive mudstone with no visible sedimentary structures.

Ichnology: No trace fossils are visible in facies 13.

Interpretation: Facies 13 was deposited under extremely low energy conditions.

Facies Nomenclature used in this thesis	Facies Nomenclature used by Downing (1986)
Facies 1-Dark gray, bioturbated silty and sandy mudstone	Facies 1-Muddy Siltstone
Facies 2-Pale gray, bioturbated, muddy siltstone and sandstone	Facies 2-Pale Siltstone
Facies 3-Interbedded pale gray, muddy sandstone and ripple laminated sandstone	No equivalent
Facies 4-Thinly interbedded pebbly, burrowed mudstone and sandstone	No equivalent
Facies 5-Pale gray, pebbly, bioturbated muddy sandstone	Facies 3-Bioturbated muddy sandstone
Facies 6-Poorly sorted coarse-grained sandstone and conglomerate	Facies 12-Conglomerates
Facies 7-Rare to moderately burrowed shales interbedded with ripple laminated sandstone	Facies 4-Burrowed, laminated sandstone/ mudstone
Facies 8-Interbedded glauconitic muddy sandstone, trough cross bedded sandstone and sideritised mudstone	Facies 5-Glauconitic-sideritic sandstone
Facies 9-Interbedded cross-bedded sandstones, bioturbated muddy sandstones and mudstones	Facies 6-Cross bedded sandstone
Facies 10-Interbedded cherty sandstone, muddy sandstone and mudstone	Possibly Facies 8-pebbly sandstone
Facies 11-Interbedded buff, silty sandstone, muddy sandstone and black mudstone	Facies 4-Burrowed laminated sandstone/mudstone
Facies 12-Hummocky cross-stratified sandstone inter-bedded sandy mudstone	Facies 10-Hummocky-bedded sandstone
Facies 13-Black mudstone	Facies 14-Black mudstone

Table 1- Facies nomenclature used in this thesis compared to that used by Downing (1986) at Joffre.

	Skolithos	*Thalassinoides*	*Diplocraterion*	*Arenicolites*	*Ophiomorpha*	*Rosselia*	*Teichichnus*	*Terebellina*	*Asterosoma*	*Subphyllochorda*	*Zoophycos*	*Rhizocorallium*	*Siphonichnus*	*Cylindrichnus*	*Schaubcylindrichnus*	*Palaeophycus*	*Planolites*	*Anconichnus*	*Chondrites*	*Helminthopsis*	*Lockeia*
Facies 1	×	×	○	×	×	◑	●	◑	○	×	○	×	○	×	×	○	●	×	◑	●	×
Facies 2	×	×	×	○	○	●	●	●	◑	◑	×	×	◑	×	◑	●	◑	●	◑	◑	×
Facies 3	×	×	○	×	◑	×	◑	◑	×	◑	×	×	×	×	×	●	◑	◑	×	×	×
Facies 4	×	○	×	○	○	×	●	×	×	×	×	×	◑	×	×	◑	●	○	×	×	×
Facies 5	◑	◑	×	◑	◑	●	×	◑	◑	●	●	×	×	×	×	●	●	◑	×	×	×
Facies 6	○	○	○	×	○	×	◑	×	×	×	×	×	×	×	×	◑	×	×	×	×	×
Facies 7	×	×	×	×	×	×	◑	○	×	×	×	×	×	×	×	◑	◑	×	×	×	×
Facies 8	◑	◑	◑	◑	○	×	×	×	×	×	×	×	×	×	×	◑	◑	×	×	×	×
Facies 9	×	◑	×	×	◑	×	×	×	×	×	×	×	×	×	×	●	×	×	×	×	×
Facies 10	×	◑	◑	×	◑	×	●	×	●	×	×	×	×	×	×	●	×	×	×	×	×
Facies 11	○	×	○	×	○	○	◑	○	×	×	×	×	×	○	×	◑	◑	×	×	×	○
Facies 12	×	◑	◑	×	◑	◑	◑	×	◑	◑	◑	○	◑	○	×	●	×	●	◑	×	○
Facies 13	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×

Table 2-Relative abundance of ichnogenera within each facies

Abundant ● Rare ○
Moderate ◑ Not observed ×

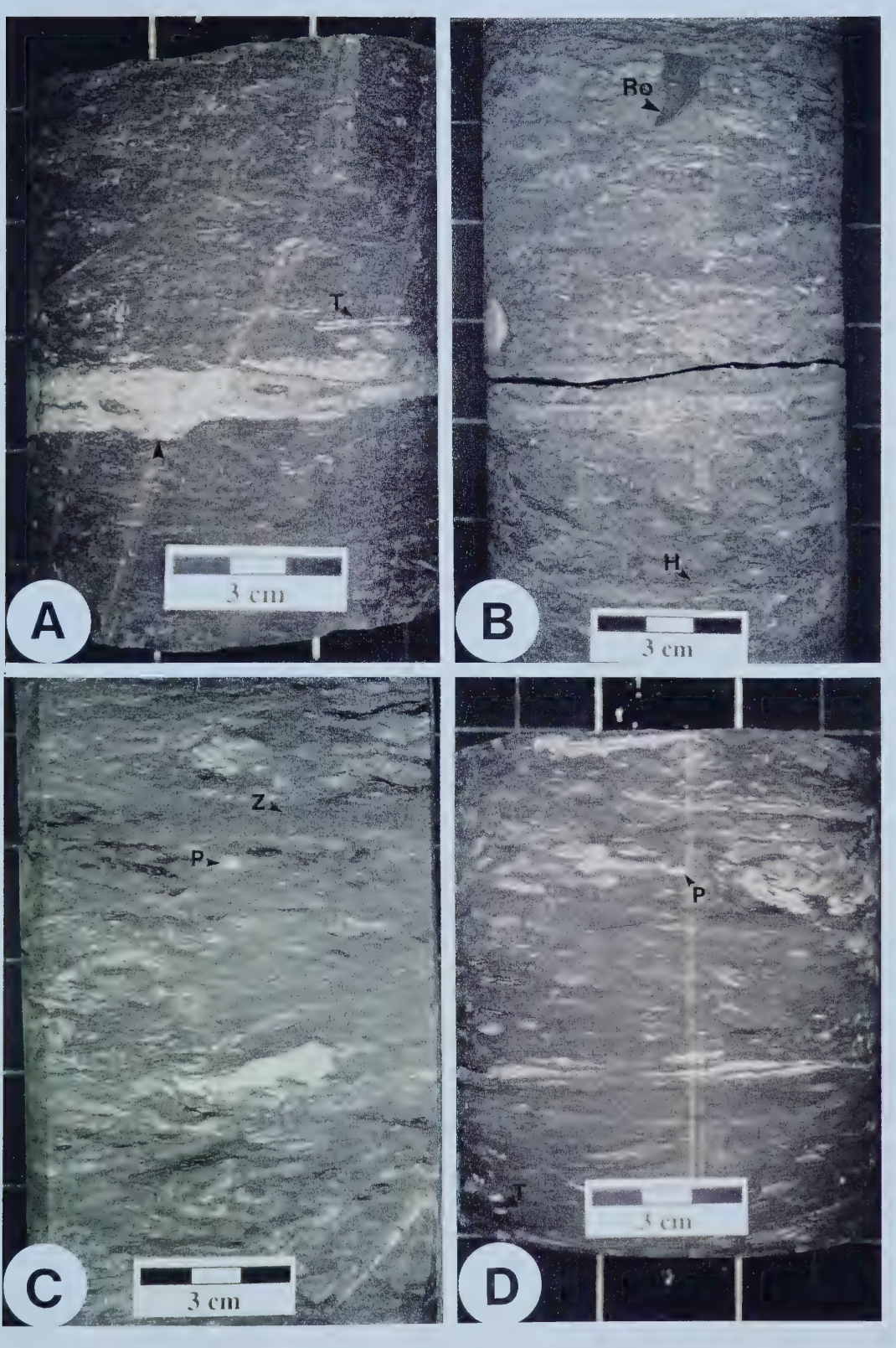
Figure 11-Facies 1: Dark gray to black bioturbated, thoroughly bioturbated, silty mudstone

(A) **7-13-37-24W4**. *Terebellina* (T) with fairly abundant *Helminthopsis*, and *Planolites*. Note how bioturbation has churned storm bed (black arrow). Depth 1381m

(B) **10-17-37-23W4**. *Rosselia* (Ro) and *Helminthopsis* (H) with *Zoophycos*, *Chondrites* and *Planolites*.. Depth 1399m.

(C) **4-32-36-21W4**. *Planolites* (P) and *Zoophycos* (Z) with *Teichichnus*, *Chondrites* and *Asterosoma*.. Depth 1343m.

(D) **7-29-36-23W4**. *Terebellina* (T) and *Planolites* (P). Depth 1465m.


A
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3 cm
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Ro
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3 cm
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P
3 cm
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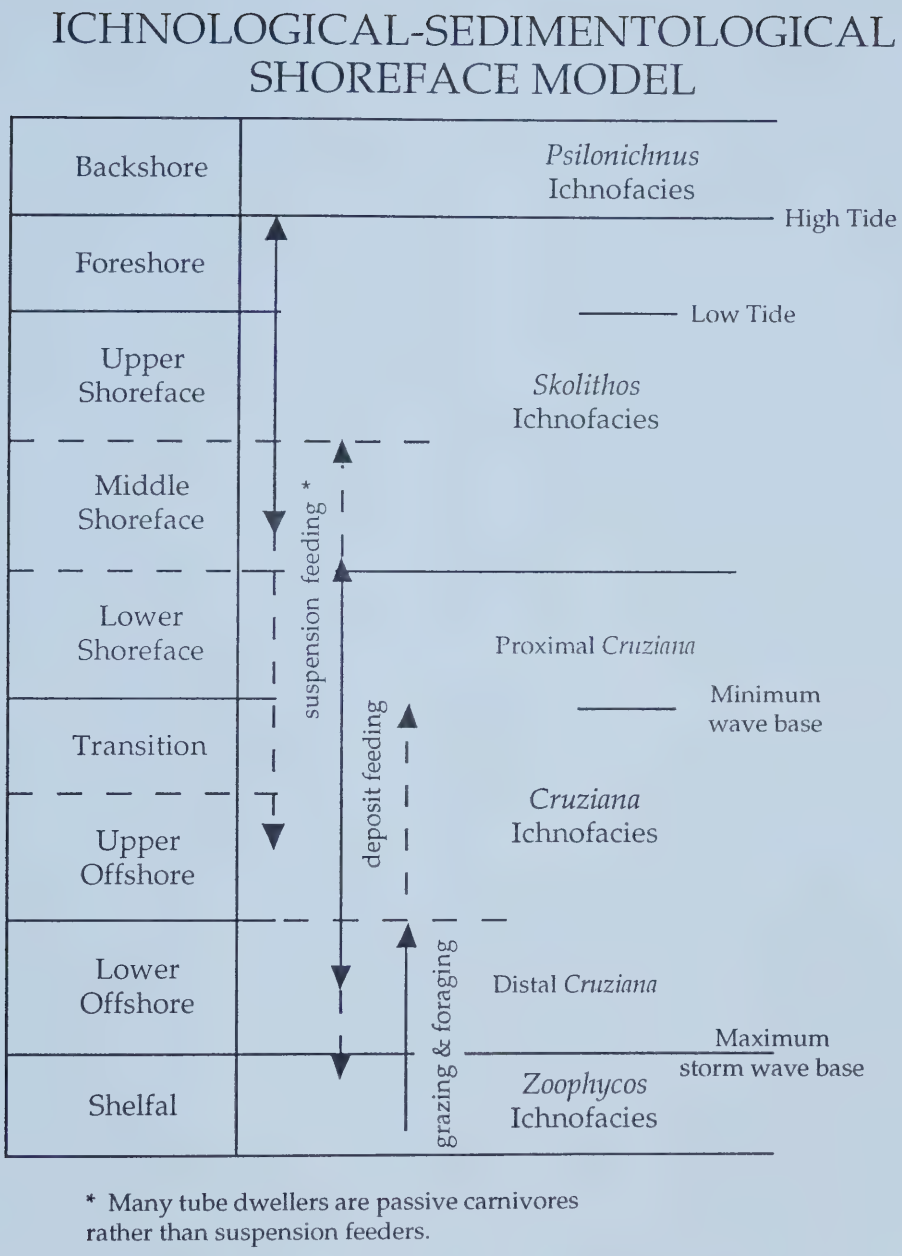


Figure 12-Idealised shoreface model of ichnofacies successions, based on observation of Cretaceous strata of the Western Interior Seaway of North America (modified after Pemberton *et al.*, 1992a).

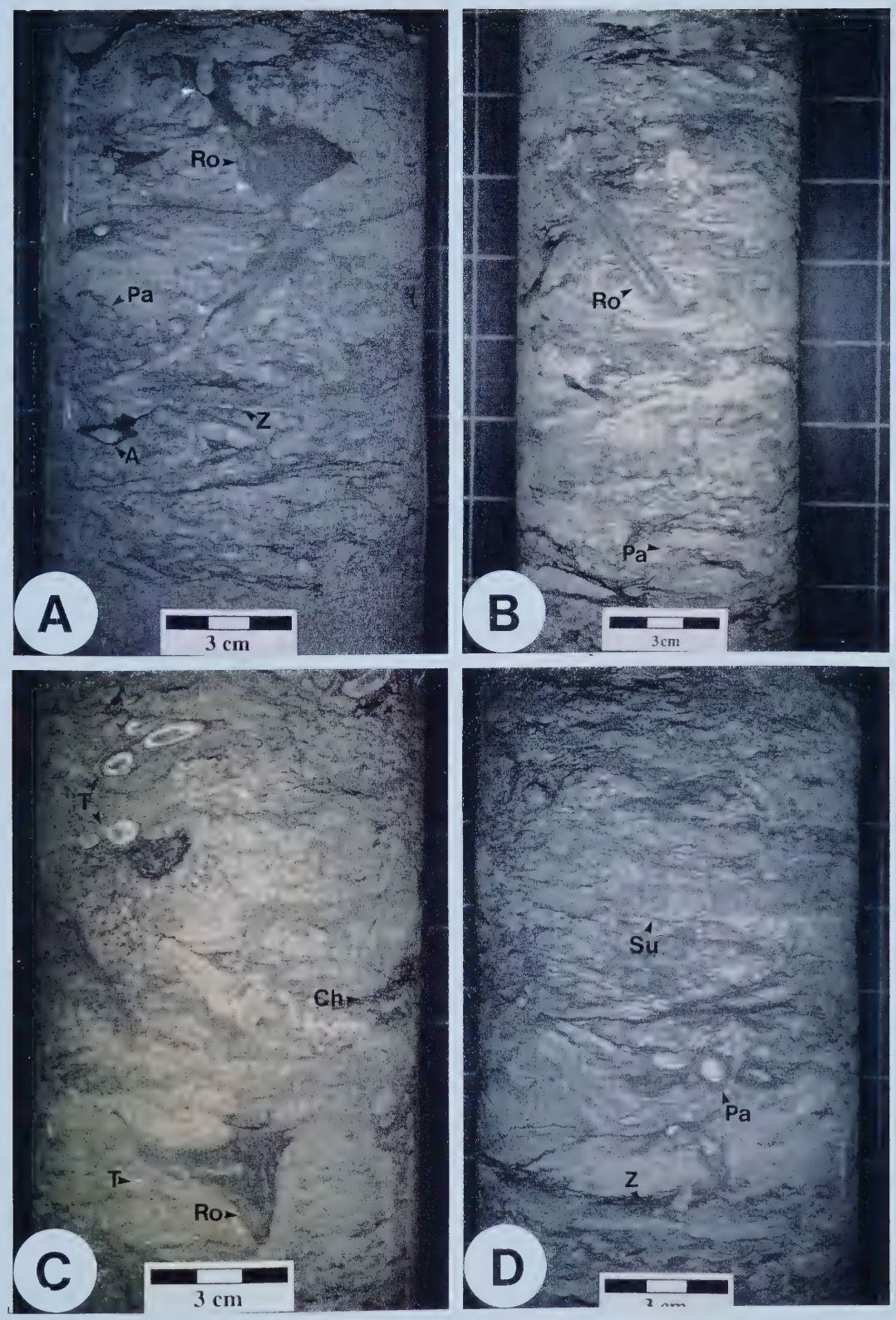
Figure 13-Facies 2: Pale gray, thoroughly bioturbated, silty sandstone and sandstone

(A) **11-13-34-20W4**. *Rosselia* (Ro), *Zoophycos* (Z), *Asterosoma* (A) and *Palaeophycus* (Pa) along with *Chondrites* and *Planolites*. White arrows show upward movement of *Rosselia*- trace-making organism, which attempted to keep up with deposition. Depth 1236.5m.

(B) **11-2-34-20W4**. *Rosselia* (Ro) and *Palaeophycus* (Pa) along with *Teichichnus* and *Chondrites* 1223m.

(C) **7-20-36-23W4**. *Terebellina* (T), *Rosselia* (Ro), *Chondrites* (Ch), and *Palaeophycus* (Pa). Depth 1470.9m.

(D) **11-13-34-20W4**. *Subphyllochorda* (Su), *Palaeophycus* (Pa) and *Zoophycos* (Z). Depth 1236.6m


Ro
Pa
Z
A
A
3 cm
Ro
Pa
B
3cm
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Ch
T
Ro
C
3 cm
Su
Pa
Z
D

Figure 14-Facies 3: Pale gray shaly sandstone and ripple laminated sandstone

(A) **10-4-34-24W4**. *Diplocraterion* (D) penetrating sharp-based, storm-generated bed. Also *Terebellina* (T) and *Palaeophycus* (Pa) are present with *Chondrites* and *Planolites*.. Depth 1485m.

(B) **10-4-34-24W4**. *Teichichnus* (Te) and *Palaeophycus* (Pa). Note remnant storm beds. Depth 1489m.

(C) **10-4-34-24W4**. *Planolites* (P), *Palaeophycus* (Pa), *Diplocraterion* (D) and *Anconichnus* (An). White arrows highlight sharp based storm bed with burrowed top. Depth 1489m.

(D) **10-4-34-24W4**. Stacked wavy parallel laminated sandstone (bottom arrow) and oscillation rippled sandstone (top arrow) defining repetitive storm bed deposition. The preservation of the waning storm ripples indicates minimal erosion and amalgamation. Depth 1484m.

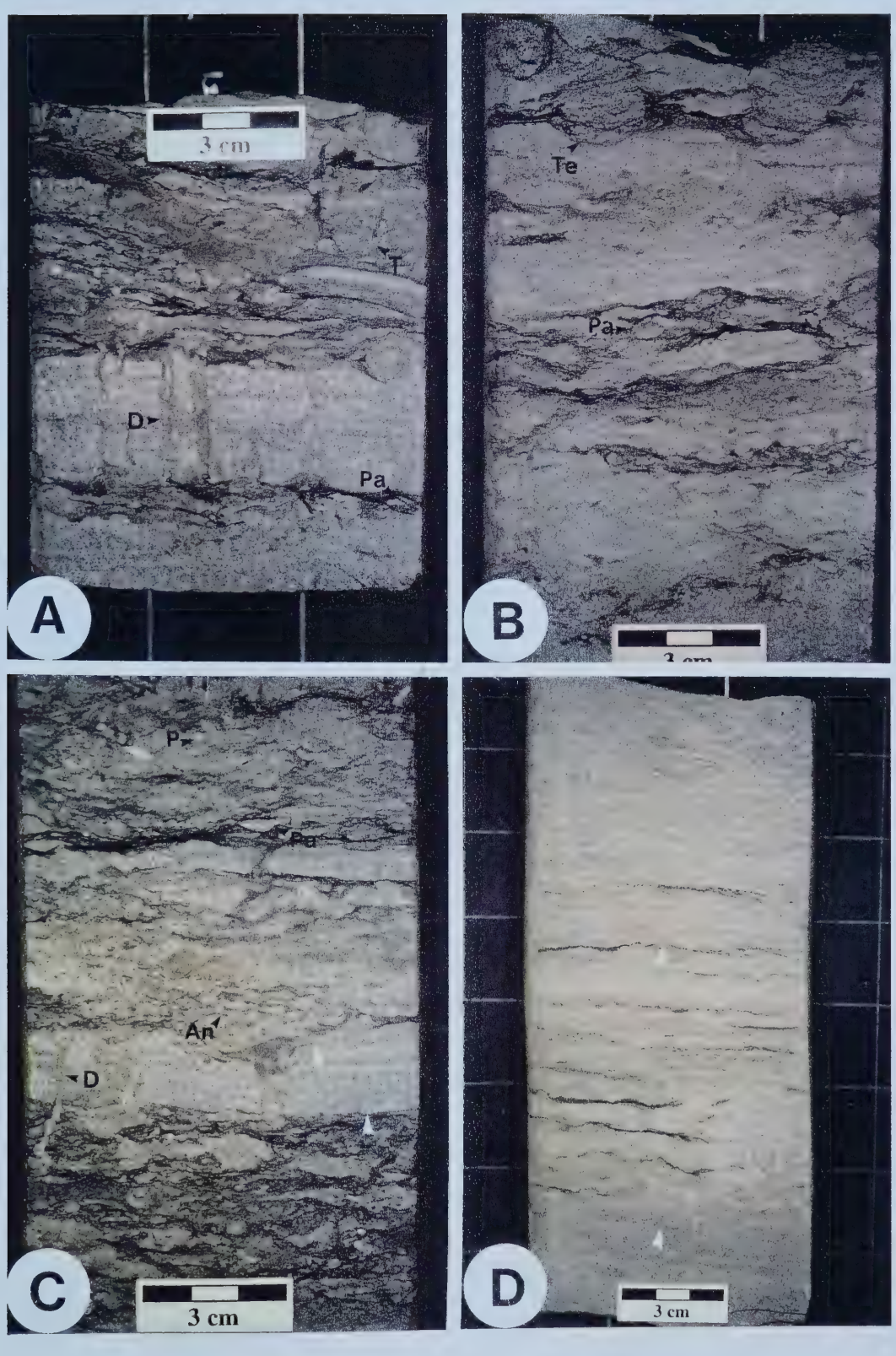

3 cm
D
Pa
A
Te
Pa
B
P
Pa
An
D
C
3 cm
D
3 cm

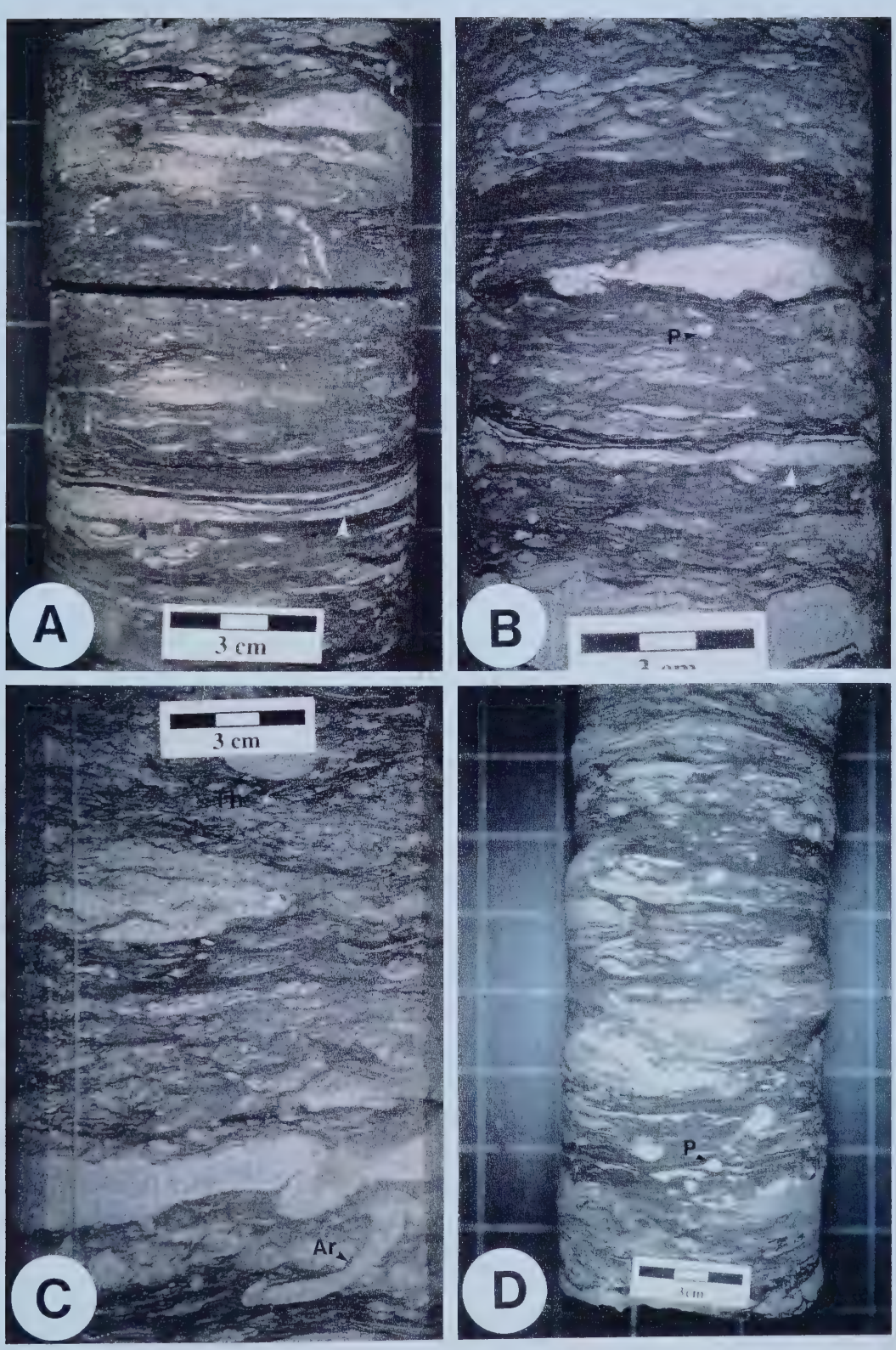
Figure 15-Facies 4: Pebbly, black, burrowed interbedded shale and fine- to medium-grained sandstone

(A) **10-17-37-23W4**. White arrow points to laminated storm bed. Depth 1398m

(B) **10-35-35-20W4**. *Planolites* (P) along with *Teichichnus* and *Chondrites*. White arrow points to bioturbated storm bed. Depth 1213m.

(C) **7-20-37-23W4**. *Thalassinoides* (T) and *Arenicolites* (Ar) along with *Teichichnus* and *Chondrites*. . Depth 1386.5m

(D) **7-18-34-18W4**. *Planolites* (P) with "shredded sandstone beds reflecting remnant tempestites and oscillation ripples. Depth 1146m.


A
3 cm
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P
C
3 cm
Ar
D
P

Figure 16-Facies 5: Pebbly, pale grey, well-burrowed shaly sandstone

(A) **10-2-37-23W4**. Thoroughly churned example of facies five. White arrow points to black chert granule. Depth 1396m.

(B) **4-32-36-21W4**. *Zoophycos* (Z), *Palaeophycus* (Pa) and *Anconichnus* (An) along with *Chondrites, Terebellina* and *Ophiomorpha*. in muddy sandstone showing gradational transition from facies four and facies five. White arrow points to black chert pebble. Depth 1341m.

(C) **12-8-34-18W4**. *Palaeophycus* (Pa), *Chondrites* (Ch) and *Terebellina* (T). Note presence of dispersed granules and pebbles throughout. Depth 1146m.

(D) **10-2-37-23W4**. *Subphyllochorda* (Su) in a thoroughly sideritized and bioturbated example of facies five, located immediately below Discontinuity Two. Depth 1396m.

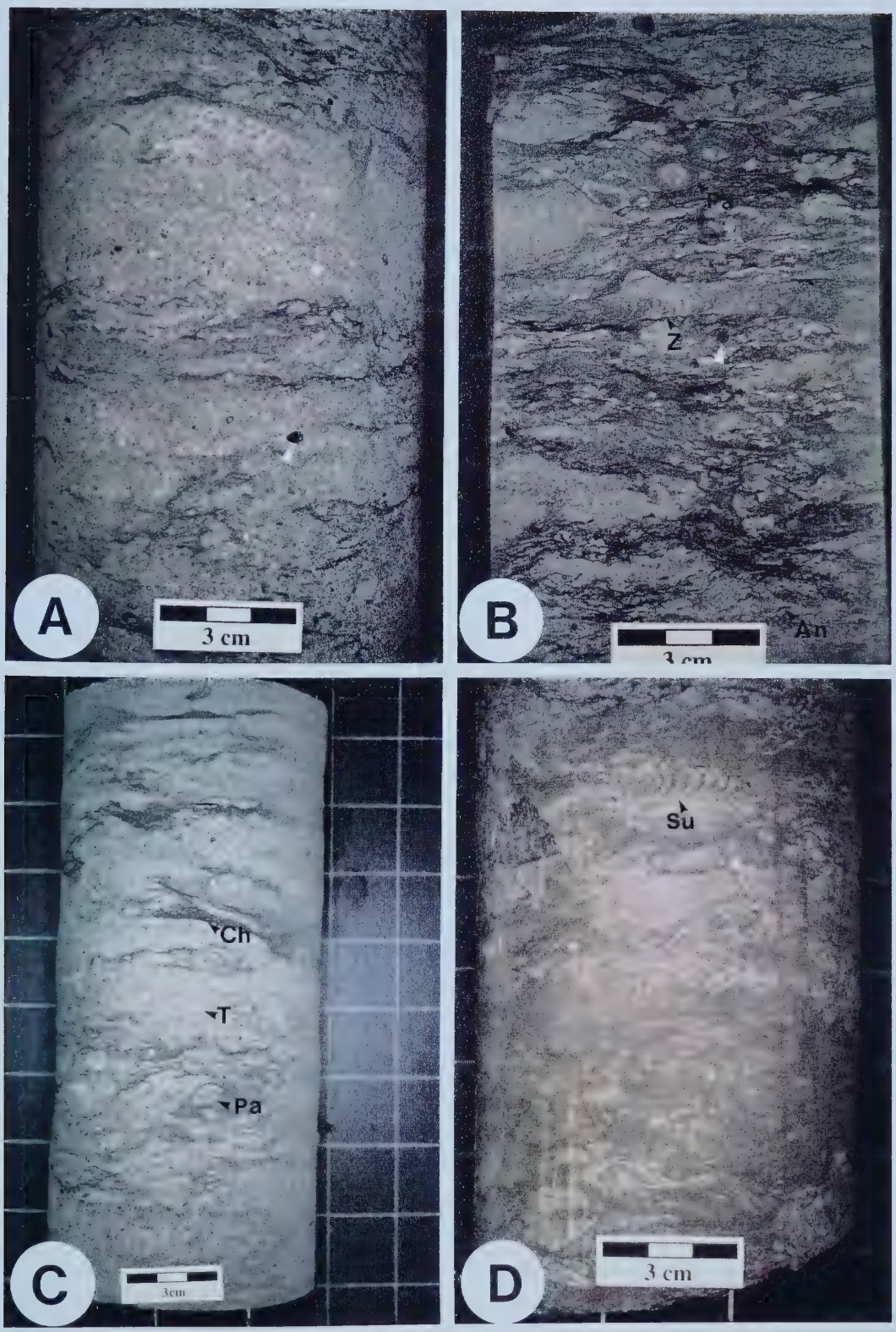
A
3 cm
B
Pa
Z
An
C
Ch
T
Pa
3cm
D
Su
3 cm

Figure 17-Facies 6: Poorly-sorted, pebbly, coarse-grained muddy sandstone and conglomerate

(A) **7-13-37-24W4**. Poorly-sorted, matrix-supported conglomerate with faint, crudely defined low angle cross-bedding. The unit is normally graded. Depth 1379m.

(B) **10-35-35-20W4**. Poorly-sorted conglomerate with sandy shale matrix. Depth 1201m.

(C) **8-2-35-20W4**. Poorly-sorted, coarsening upwards clast-supported conglomerate. Depth 1194m.

(D) **10-8-37-23W4**. Poorly-sorted coarse-grained sandstone grading into a clast-supported conglomerate. Depth 1388m.

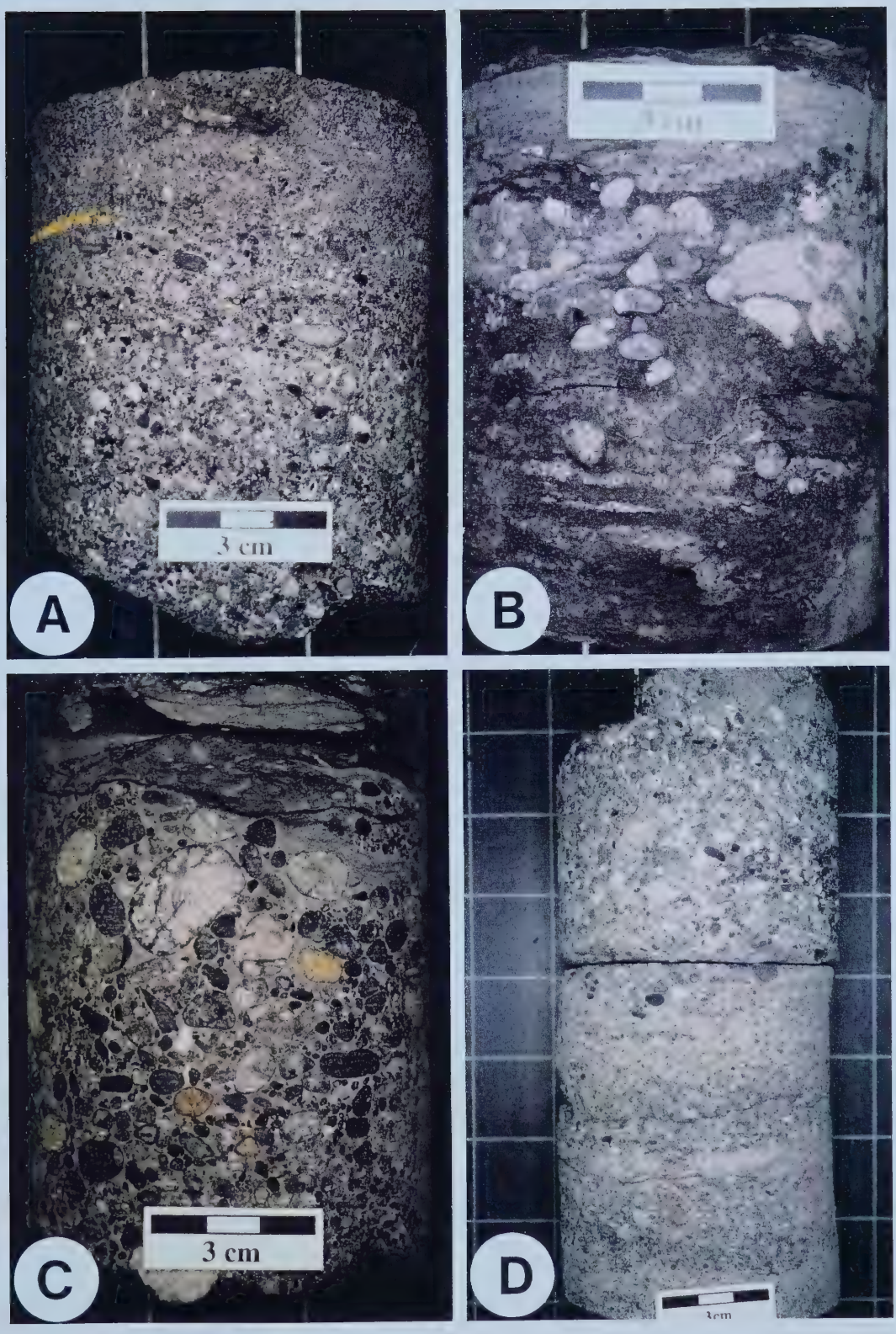
3 cm
A
B
3 cm
C
D

Figure 18-Facies 7: Rarely to moderately burrowed shale, interbedded with rippled sandstone

(A) **10-30-37-23W4**. *Planolites* (P). Wavy parallel laminated and oscillation rippled fine-grained sandstone beds. White arrows point to oscillation ripples. Depth 1371m.

(B) **4-32-37-23W4**. Preserved distal storm deposits (white arrow) in an overall stressed trace assemblage of *Planolites* and *Palaeophycus* . Depth 1338m.

(C) **4-32-37-23W4**. Oscillation ripple laminated sandstone beds encased in generally unburrowed sediments. The lack of bioturbation and diminutive traces indicate a stressed environment of deposition. Depth 1339.7m

(D) **11-13-34-20W4**. *Palaeophycus* (Pa) and *Teichichnus* (Te) dominated trace assemblage. Note synaeresis crack (white arrow) a further indicator of possible salinity variations. Depth 1234m.

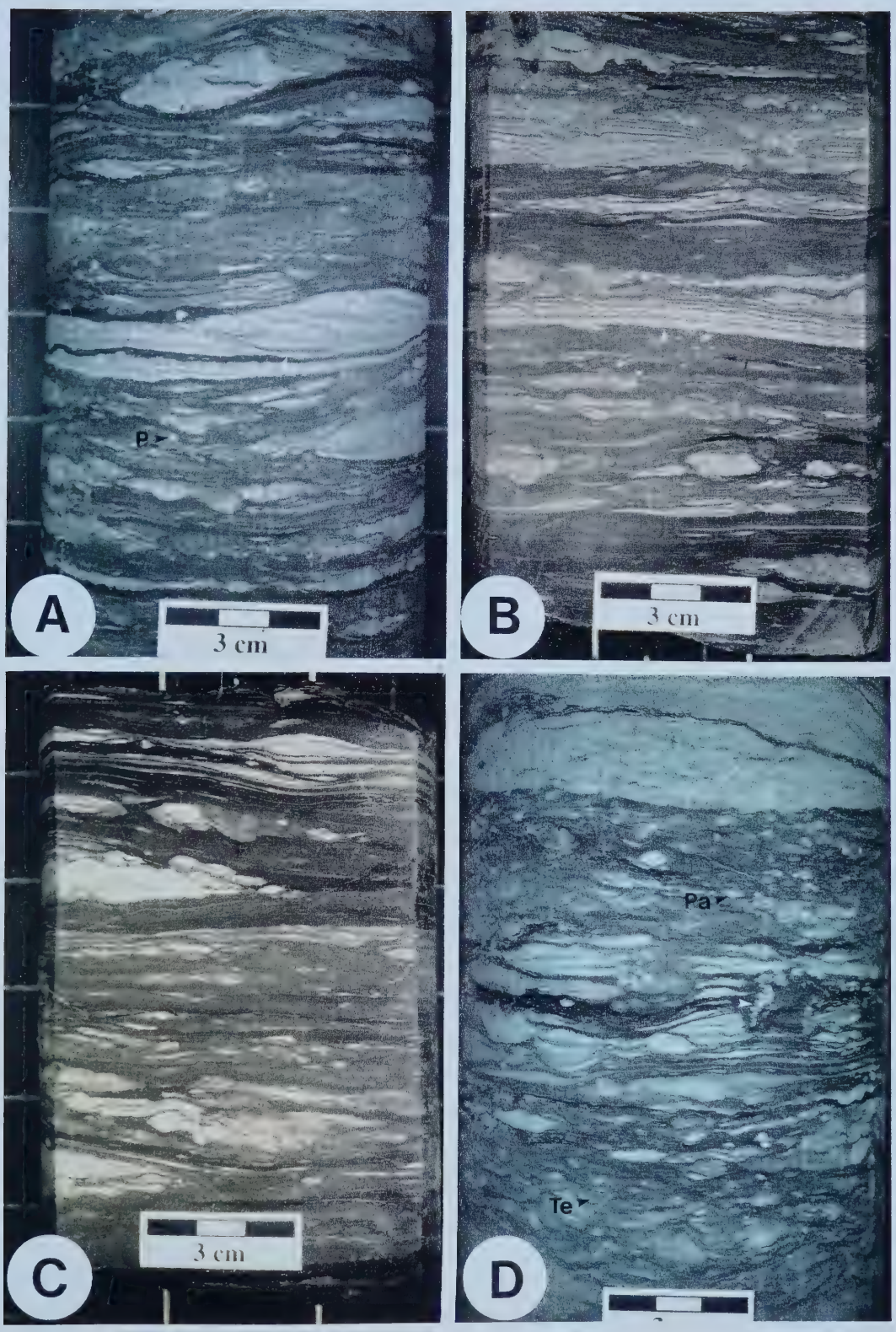
A
P
3 cm
B
3 cm
C
3 cm
D
Pa
Te

Figure 19-Facies 8 Interbedded glauconitic muddy sandstone, trough cross-bedded sandstone and sideritized mudstone

(A) **11-2-34-20W4**. Glauconitic trough cross-bedded sandstone, interbedded with sideritized mudstone (white arrow). Note small sand filled *Planolites* at the top of the sideritized mud bed. Depth 1218m

(B) **10-16-37-24W4**. Trough cross-bedded sandstone with foresets (white arrow) highlighted by glauconite and carbonaceous material. An oblique section of a *Skolithos* (below the arrow) supports a marine influence on deposition. Depth 1442m

(C) **11-13-34-20W4**. Rounded, sideritized mudstone clasts in toeset of trough cross bedded sandstone. Note sideritized mudstone and bioturbated muddy sandstone below. Depth 1228m.

(D) **7-1-37-24W4**. *Ophiomorpha* (O) along with *Planolites* and *Palaeophycus* below partially sideritized, well-bioturbated muddy sandstone. Depth 1415m.

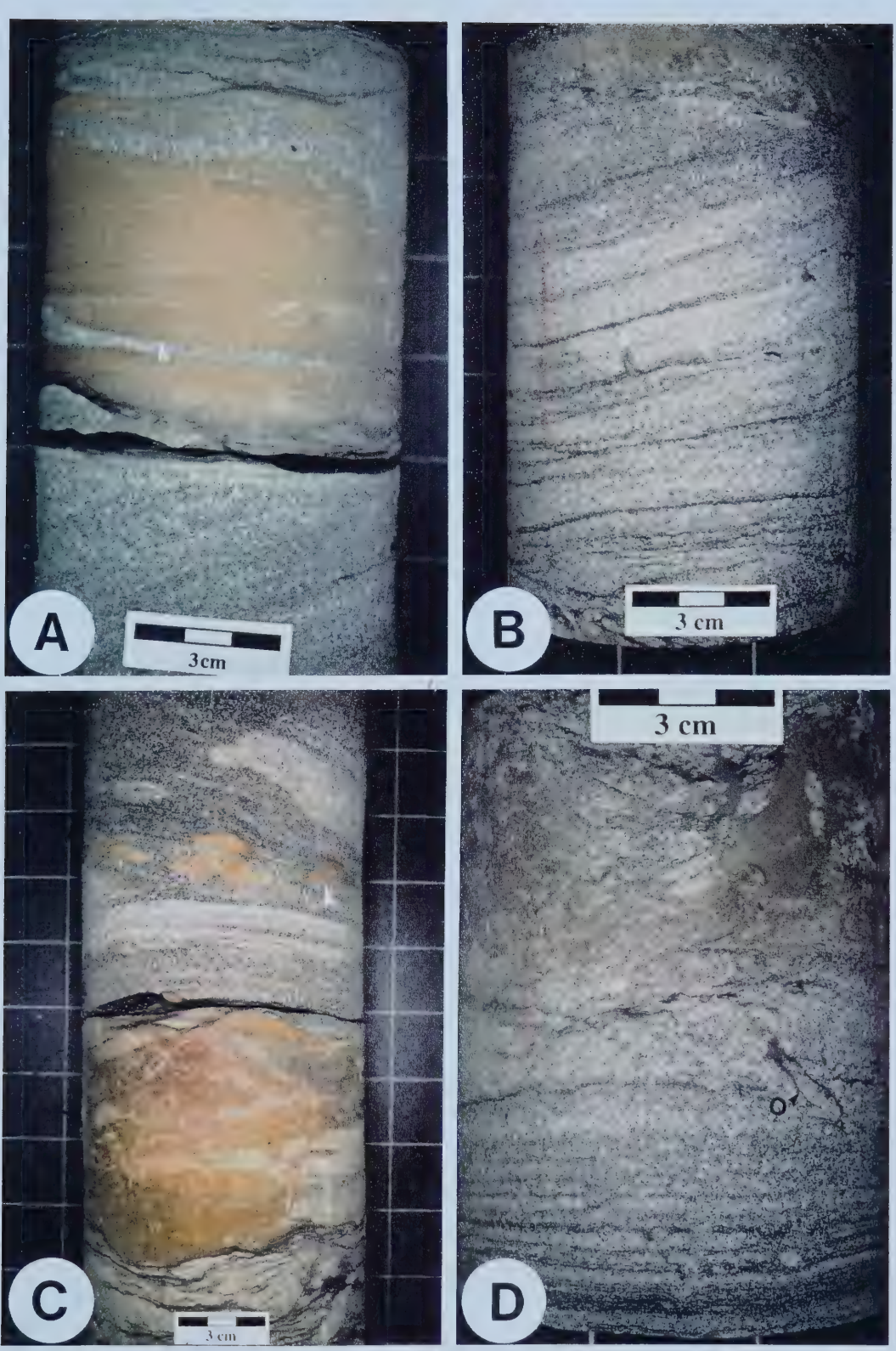
A
3cm
B
3 cm
C
3 cm
D
3 cm

Figure 20-Facies 9: Interbedded cross-bedded sandstone, bioturbated muddy sandstone and mudstone

(A) **2-33-34-20W4**. Sideritized mudstone bed (white arrow), muddy interlaminae and rounded, sideritized mudstone rip-up clast (black arrow) in cross-bedded sandstone. Depth 1196m.

(B) **7-1-37-24W4**. Coarse grained trough cross-bedded pebbly sandstone. Note the higher angle of foresets (~30 degrees). Depth 1412m.

(C) **10-35-35-20W4**. Faint, low angle planar stratification. *Planolites* occurring in muddy beds towards top of unit. Depth 1208.5m

(D) **10-3-32-17W4**. *Ophiomorpha* (O) and *Palaeophycus* (Pa) in muddy portion of unit along with *Chondrites,* and *Planolites*.. Note unsideritized mudstone bed at top of photo (white arrow). Black arrow points to a large sideritized mudstone rip-up clast. Depth 1086m.

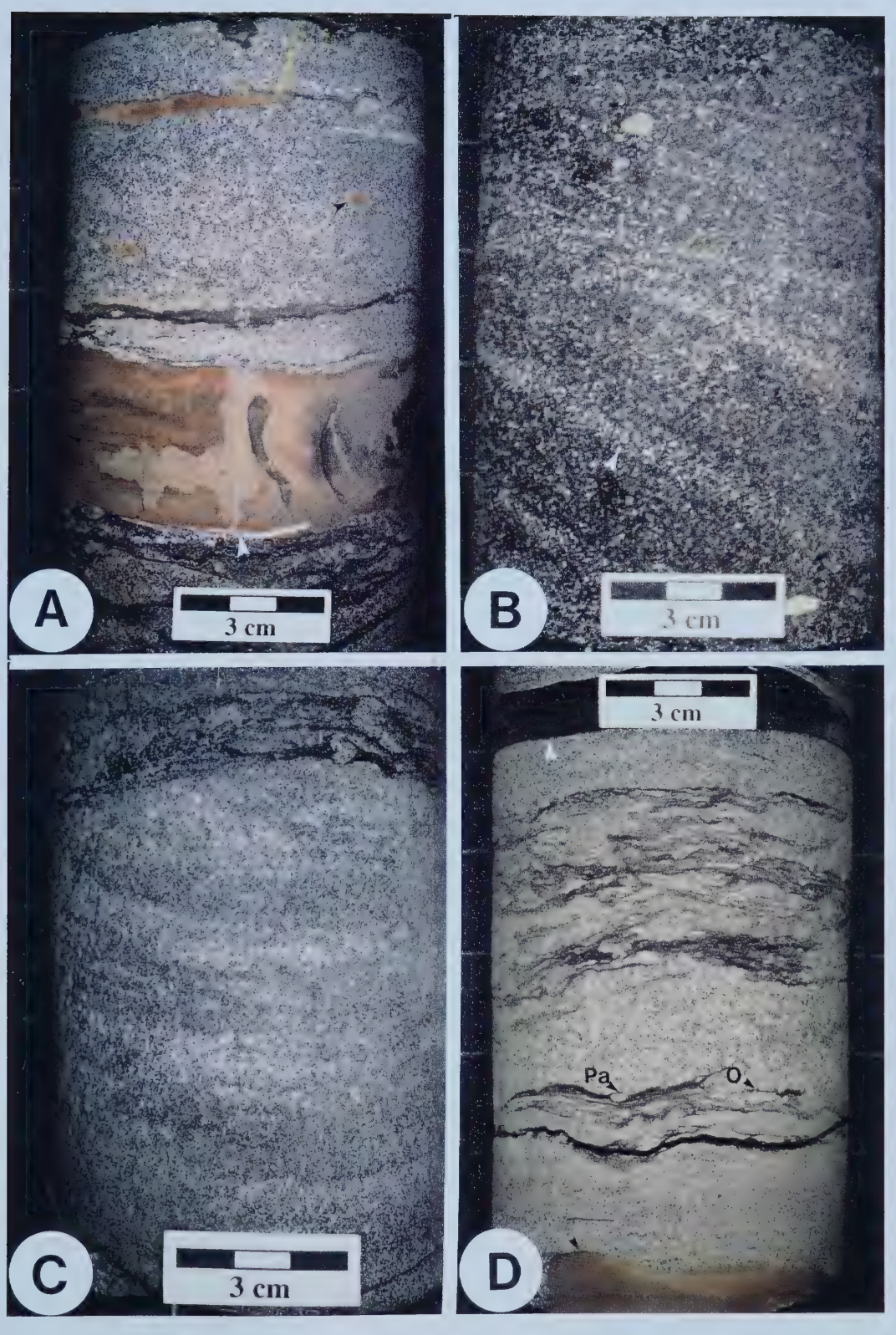
A
3 cm
B
3 cm
C
3 cm
D
3 cm
Pa
O

Figure 21-Facies 10: Interbedded cherty sandstone, muddy sandstone and mudstone

(A) **3-18-37-23W4**. Apparently structureless massive cherty sandstone with organic mudstone interlaminae. Depth 1376m.

(B) **10-30-37-23W4**. Cherty sandstone with mudstone interbeds and interlaminae burrowed with *Diplocraterion* (D), *Planolites* and *Teichichnus*. Depth 1370m.

(C) **10-15-36-22W4**. *Lockeia* ? along with (black arrow) occurs in burrowed muddy sandstone below cross-bedded cherty sandstone (white arrow). Depth 1357m.

(D) **10-30-37-23W4**. Current rippled cherty sandstone with muddy interbeds. Depth 1372m.

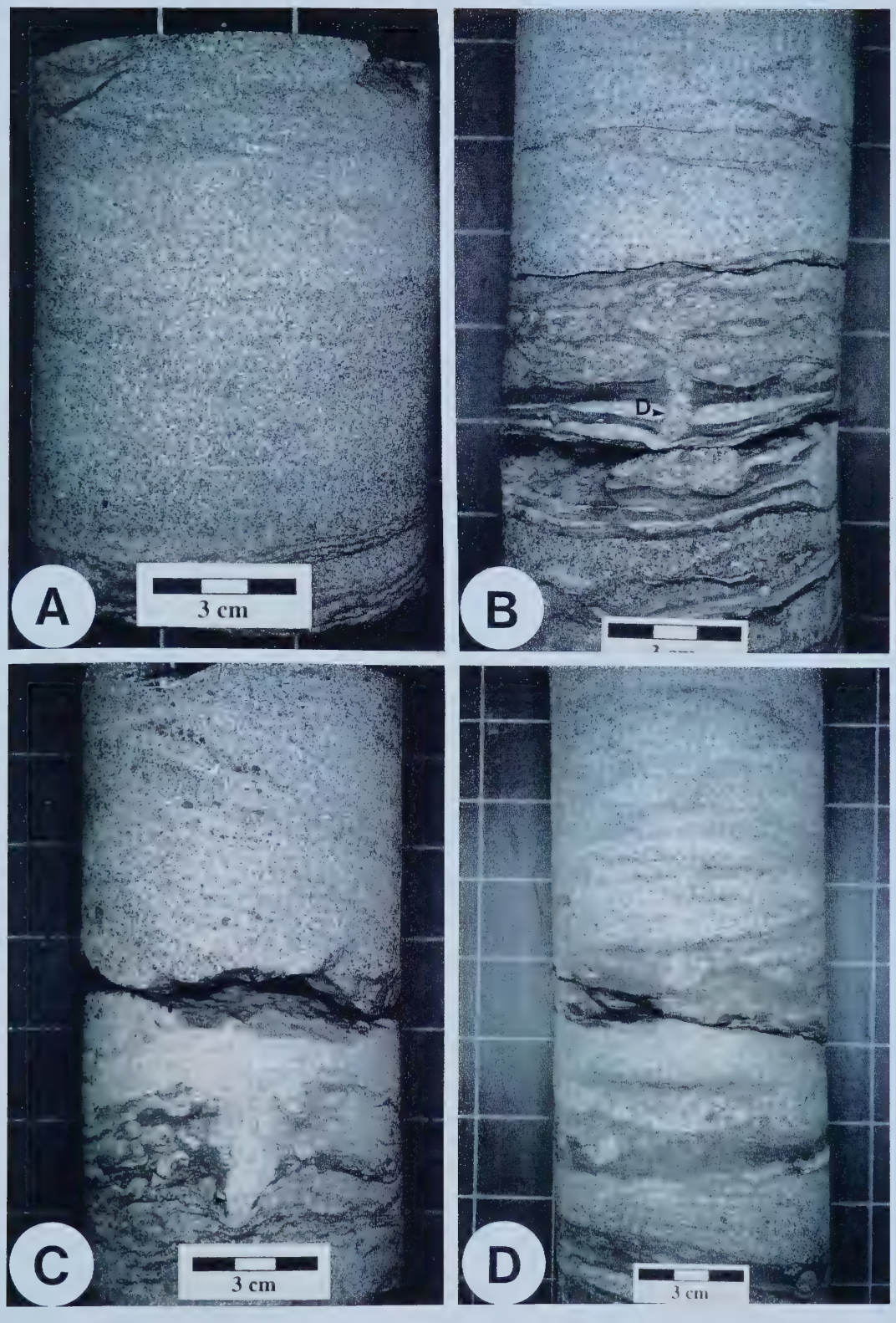
A
3 cm
B
D
C
3 cm
D
3 cm

Figure 22-Facies 11: Interbedded buff-colored silty sandstone, bioturbated muddy sandstone and black mudstone

(A) **3-31-36-22W4** *Lockeia* (L), current ripples (white arrow) and oscillation ripples (black arrow) and wavy parallel laminated sandstone bed in a example of facies eleven, displaying a low burrowing intensity. Depth 1399m.

(B) **7-29-36-23W4**. Moderately burrowed interval with thin tempestite bed disrupted by *Diplocraterion* and escape trace. *Teichichnus, Planolites, Chondrites* are also present. Depth 1461m.

(C) **7-13-37-24W4**. White arrows point to sharp transition from high burrowing intensity to low burrowing intensity. Highly burrowed zone contains *Planolites* and *Teichichnus.* Depth 1373.5m.

(D) **8-1-36-22W4**. Well burrowed example of facies eleven. Note presence of diminutive *Terebellina* (T). Depth 1283m.

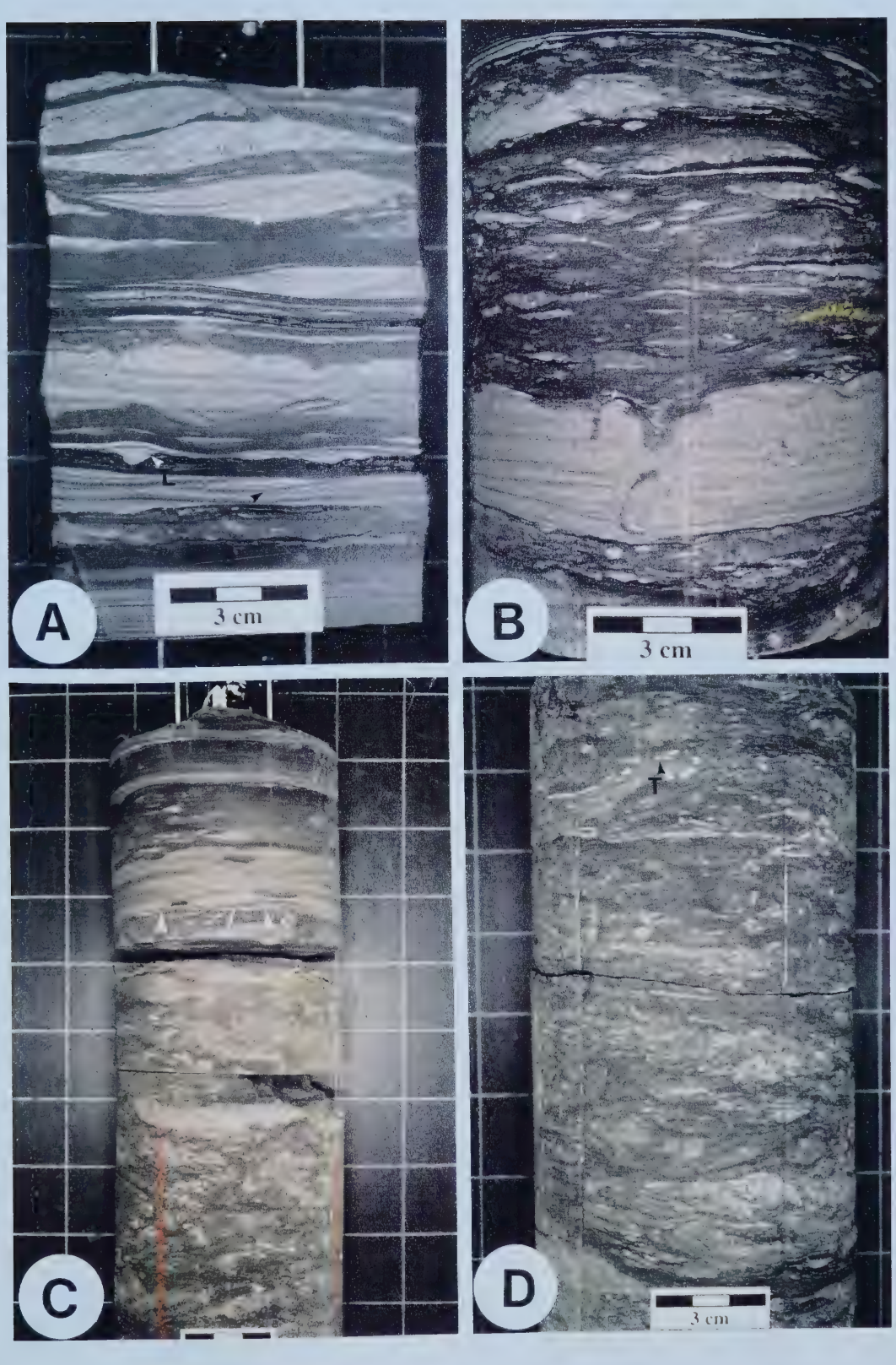
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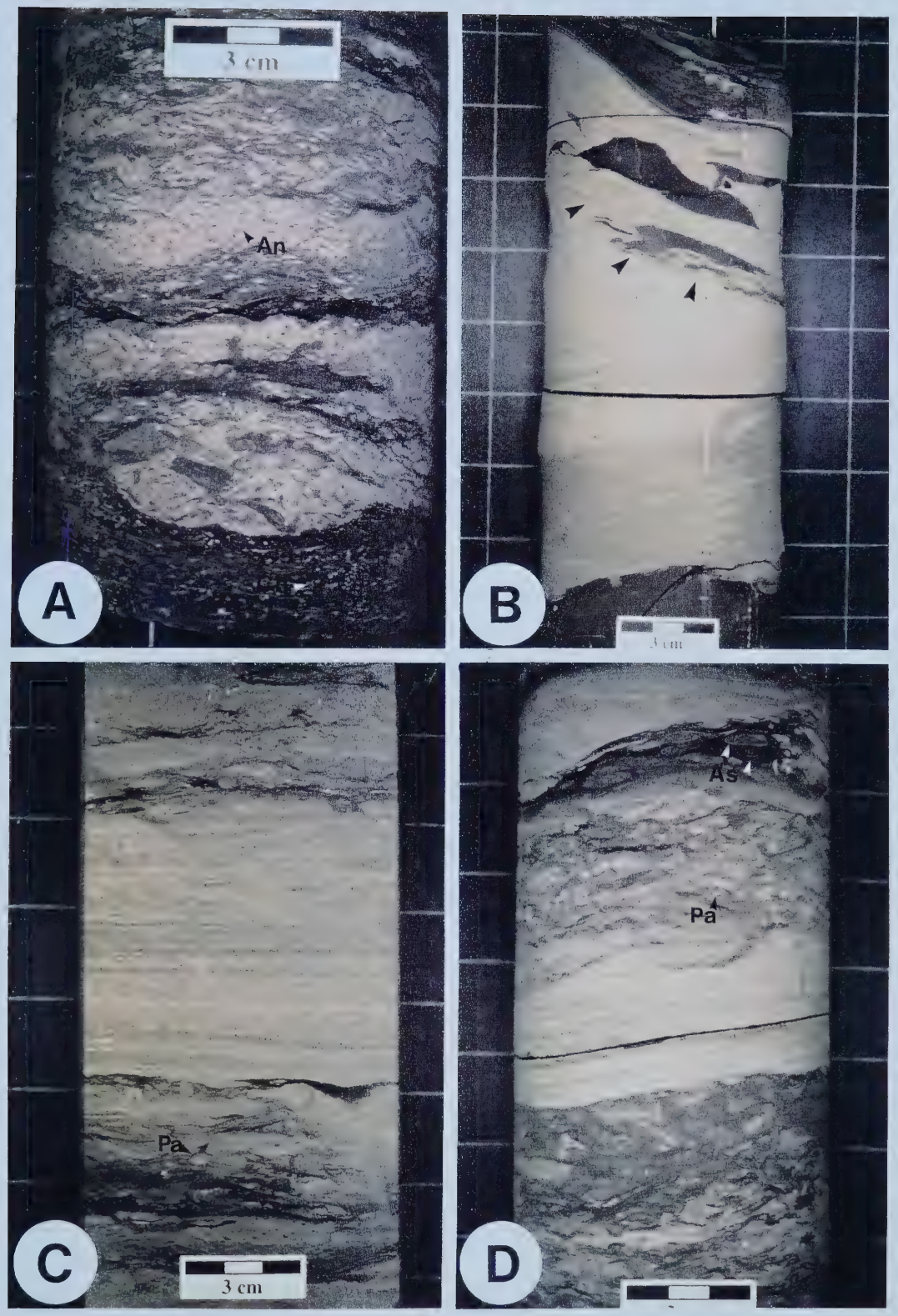
Figure 23-Facies 12: Hummocky cross-stratified sandstone, interbedded with muddy sandstone

(A) **2-33-34-20W4**. Bioturbated muddy sandstone with shale interbeds containing abundant *Chondrites* (Ch), and *Anconichnus* (An). Depth 1190m.

(B) **11-6-33-20W4**. Hummocky cross-stratified to swaley cross-stratified sandstone with laminae truncated by probable gutter cast (black arrows). Mudstone rip-up clasts mantle the scour surface. Depth 1195.7m.

(C) **7-1-32-20W4**. Laminated to burrowed sandstone. Laminae reflect storm-generated hummocky cross-stratification. Burrowed sandstone corresponds to fairweather deposition, with *Palaeophycus* (Pa) *Chondrites,* *Asterosoma* and *Helminthopsis.* Depth 1404m.

(D) **10-7-32-20W4**. Laminated to burrowed sandstone with *Asterosoma* (As) and *Palaeophycus* (Pa). Note how the top of the sharp based storm deposited bed has been burrowed during the return to fairweather conditions. Depth 1207.6m.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D

CHAPTER THREE: DESCRIPTION OF FACIES ASSOCIATIONS AND EROSIONAL SURFACES

3.1: Introduction

Chapter two dealt with the most elemental components of the succession, the facies. While it was relatively simple to subdivide the Viking Fm into its constituent parts, it is quite another matter to correlate individual facies throughout the study area or to attach any significance to the successions of facies found in each drill core. Facies in the study area were commonly found in similar, recurring packages. These packages constitute facies associations and five such facies associations occur in the study area.

The recognition of distinct groups of facies, or facies associations, enables correlation and mapping to have value. Each of the facies associations in the study area, with the exception of Facies Association One, are bound by erosional discontinuities. These erosional discontinuities are referred to in this study, in ascending stratigraphic order, as Discontinuity 3, Discontinuity 2, Discontinuity 1 and Viking Erosion Surface Four (VE4).

This chapter describes the nature and composition of each facies association and the erosional discontinuities that bound them. The end of chapter three offers examples of the facies associations and erosional surfaces in drill core from the Mikwan, Fenn, and Chain fields. Many of the facies associations, in like manner to the facies described in chapter two, are similar to the facies associations described (Downing and Walker, 1988) at Joffre. Table 3 compares the facies association and erosional surface terminology used by Downing and Walker (1988), Boreen and Walker (1991), Pattison (1991) and that used in this thesis.

3.2: Facies Association 1-The Regional Viking Facies Association

Facies Association 1 (FA1) forms the lowermost and oldest deposits of the Viking Fm in the study area (Table 4). FA1 is composed of coarsening- and sanding-upwards succession of Facies 1, 2 and 3, deposited in a fully marine environment with a diverse and abundant trace assemblage (Table 5). Erosion has removed Facies 3 in the Mikwan, Fenn West, Fenn Big Valley and Chain fields and was only observed in one well to the southwest (10-24-

34-24W4). FA1 in other cored wells is made up of stacked successions of Facies 1 and 2 with little or no variability. Contacts between all facies are gradational, and no evidence of erosion between facies was observed. The thickness of FA1 ranges from 27m in the southwest of the study area, thinning to 8 m in the area of the above mentioned Viking gas fields. Sanding upwards successions of Facies 1 and Facies 2 form regionally extensive progradational parasequence sets in the study area. The top of each parasequence also contains a bentonite bed. The top of the lower parasequence contains a 20-30 cm thick, bentonite horizon, while the bentonite bed at the top of the uppermost parasequence is only 2-5cm thick. Because of the bentonite beds contained in them, both of these parasequences have distinctive well log signatures that serve as useful, regionally extensive well log markers. FA1 is interpreted to constitute the Regional Viking deposits in the study area and is similar to basal Viking deposits described at Joffre (Downing and Walker, 1988; MacEachern *et al.*, 1995a,b), central Alberta (Pattison, 1991) and at Kaybob (MacEachern, 1994).

3.3: Discontinuity 3

Discontinuity 3 separates FA1 and the overlying sediments of Facies Association 2 (FA2). Discontinuity 3 is sharp and erosive in nature and is demarcated in many drill cores by a pebble lag and the *Glossifungites* ichnofacies (Fig. 24).

The *Glossifungites* ichnofacies is a substrate-controlled ichnofacies and is characterized by robust, unlined vertical and subvertical burrows, passively infilled by sediments from the overlying unit (Frey and Seilacher, 1980; MacEachern *et al.*, 1992). The substrate, which is typically a mudstone or shale, was obviously firm and cohesive before it was colonized by the *Glossifungites*-trace making organisms. If the substrate was not firm and cohesive, the unlined burrows would collapse before the overlying sediments could infill them. This implies that a depositional hiatus occurred between the erosion of the substrate, its subsequent colonization by opportunistic *Glossifungites*--trace making organisms and the deposition of the overlying unit. Another characteristic of the *Glossifungites* ichnocoenose is the high density of burrows. Burrow densities of 1100 to 2300 shafts per m^2 have been observed in the Viking Fm (MacEachern, 1994), while similar densities have

been observed on ravinement surfaces developing on the modern Georgia coast (Pemberton and Frey, 1985). Dense populations are typical of many opportunistic ichnocoenoses (Pemberton and Frey, 1984).

The succession of events that leads to the creation of a *Glossifungites* ichnofacies is summarized as follows: 1) burial of the shales or mudstones and their subsequent dewatering results in the development of a firm, cohesive substrate 2) relative sea level falls, followed by transgression 3) the substrate is erosionally exhumed during transgression 4) the surface is colonized by opportunistic *Glossifungites* -trace making organisms and resumption of deposition and the infilling of dwelling burrows (Fig. 25). A *Glossifungites* ichnofacies commonly demarcates erosive surfaces of stratigraphic significance as it forms during a depositional hiatus and indicates that overlying sediments have no genetic affinity with the underlying unit.

3.4: Facies Association 2-Pebbly Sandstone Facies Association

Facies Association 2 (FA2) erosively overlies FA1, separated by Discontinuity 3 at its base and at the top by either Discontinuity 1 or Discontinuity 2. It has no genetic affinity with FA1. FA2 is found in 65% of the cored wells in the study area (Table 4) and ranges from 1-7m in thickness.

Within FA2, facies successions are variable, but can be broken down into three stacking patterns. Of the cored wells displaying FA2, 20% have conglomerates of Facies Six overlying Discontinuity 3, followed by a gradational change into the pebbly sandstones of Facies Five. A further 20% of the wells have Facies Four overlying Discontinuity 3, with a gradational transition into Facies Five. The remaining cored wells of FA2 display Facies Five only. All contacts between facies within FA2 are gradational.

The abundant and diverse trace fossil assemblage in FA2 (Table 5), the storm generated beds of Facies Four, and the thoroughly churned fabric of Facies Five, suggests that FA2 was deposited in a fully marine setting, in a lower offshore to upper offshore setting. The conglomerates of Facies Six are interpreted to be lag deposits directly overlying Discontinuity 3, reflecting wave ravinement. The dispersed pebbles found throughout FA2 may have been sourced from conglomeratic shoreface deposits and transported to the

offshore by storm generated currents, or cannibalized from coarse fluvial deposits during transgressive reworking.

3.5: Discontinuity 2

Discontinuity 2, is a sharp and erosive surface, in many localities demarcated by the *Glossifungites* ichnofacies (Fig. 26). Below the discontinuity sediments of FA2 may be pervasively sideritised for up to 0.5 m. Discontinuity 2 erosively separates FA2 from overlying deposits of FA3.

3.6: Facies Association 3- Cross Bedded Facies Association

Facies Association Three (FA3) is present in 55% of the cored wells in the study area and is composed of Facies 7, 8, 9 and 10. The sediments of FA3 erosively overlie either deposits of FA1 (in 5% of the total wells), or FA2 (50% of the total wells) (Table 4) and are bound at the base by Discontinuity 2 and at the top by Discontinuity 1. FA3 varies in thickness from 0.5 m to 9 m, with an average thickness of 2 m.

The succession and occurrence of facies within FA3 is highly variable and they are interbedded, in most cases, in a wide variety of ways. Facies 7 however, when present, is always found at the base of FA3. The deposits of FA3 have three main characteristics: 1) they are dominated by cross-bedded, medium-grained sandstones, which are interbedded with mudstones and muddy sandstones, 2) contacts between facies are sharp, 3) and trace fossil assemblages are not as diverse or as robust as in FA2 and FA1 (Table 5).

Assigning a depositional environment to FA3 is problematical, because of the presence of current-generated, cross-bedded, coarse-grained clastics interbedded with mudstones and bioturbated muddy sandstones. The cross-bedding and imbricated rip-up clasts indicate deposition by traction currents, powerful enough to rip up clasts from the underlying mudstones. Erosion alternated with low energy conditions that allowed the deposition of the mudstones.

If FA3 was deposited in a shoreface environment, it would fall into the upper shoreface, as indicated by the medium-grained, trough cross-bedded sandstones. However, it is highly unlikely that mudstone interbeds and interlaminae, as well as muddy sandstones interbeds would be preserved, or

even deposited, in this environment. Further the sustained high energy conditions of the upper shoreface are unlikely to have permitted the survival of non-resistant mudstone rip-up clasts. Other evidence against a shoreface environment lies in the trace fossil assemblage. Trace fossils within this assemblage are restricted both in size and diversity, especially in comparison with FA1 and Two (Table 5). The restricted trace fossil assemblage and the presence of synaeresis cracks indicates a brackish-water environment. Tidal currents could be responsible for many of the features present in FA3. The deposits of FA3 are interpreted to represent shore-normal and shore-parallel tidal channels and creeks which fed fluvially-transported, coarse-grained clastics to a sheltered embayment. This interpretation would explain the deposition of mudstones, deposited during periods of low energy, interbedded with current generated crossbeds. It would also explain the restricted trace fossil assemblage and synaeresis cracks which would result from the variable salinities common in tidal environments.

3.7: Discontinuity 1

Discontinuity 1 is sharp, erosive, and only rarely demarcated by the *Glossifungites* ichnofacies. Discontinuity 1 erosively separates the overlying deposits of FA4 from the underlying sediments of either FA1, FA2 or FA3 (Fig. 27). Deposits immediately below Discontinuity 1 may be pervasively sideritised.

3.8: Facies Association 4-Interbedded shales sandstone and muddy sandstone Facies Association

FA4 is found in all the cored wells in the study area (Table 4), and is composed of Facies 6, 11 and 12. It varies in thickness from 6 to 9m. Within FA4, Facies 6 may be found at the base followed by Facies 11 and Facies 12. Contacts between facies are sharp. Trace fossil assemblages (Table 5) increase both in diversity and robustness from the base to the top of FA4.

FA4 was deposited in a lower offshore to lower shoreface environment. Transgressive ravinement concentrated the conglomeratic lag of Facies 6 on Discontinuity 1, and continued transgression led to the deposition of the offshore interbedded sandstones and shales of Facies 11.

The increased sand content of Facies 12 and increase in bioturbation may indicate a general reduction in the rate of transgression towards the top of FA4.

3.9: VE4- Viking Erosion Surface Four

Viking Erosive Surface Four (VE4) is a regionally extensive erosive surface found at the top of the Viking Fm as described by Hadley, (1992); Pattison, (1991); Boreen and Walker, (1991). In the study area, it separates the underlying deposits of FA4 from the overlying sediments of FA5 (Fig. 28). VE4 may be demarcated by the *Glossifungites* ichnofacies.

3.10: Facies Association 5-Conglomerates and Pebbly Sandstone Facies Association

The unit overlying the VE4 surface has been documented in the subsurface throughout much of Alberta. In the study area, FA5 is present in all cored wells and consists of Facies 6 and 13. It ranges in thickness from 0.1 m to 3 m. In some wells, Facies 6 may be overlain by Facies 13, which in turn is erosively overlain by another interval of Facies 6. More commonly though, FA5 is only represented by Facies 6. Trace fossils are rarely present in FA5 (Table 5).

FA5 represents a lag deposit on top of the VE4. The presence in some wells of a Facies 6-13-6 succession may indicate that another erosive surface is part of FA5. Wells that do not demonstrate such a succession may indicate that these surfaces may have amalgamated with the underlying VE4 surface to form a single surface.

3.11: Colorado flooding surface and shales of the Westgate Fm

The top of the Viking Fm in the study area is capped by a regionally extensive flooding surface and the thick marine shale deposits of the Westgate Fm. The Colorado flooding surface is erosive and defines the top of the Viking Fm. It may be associated with a conglomeratic lag and be demarcated by the *Glossifungites* ichnofacies (Fig. 28a).

3.12: Facies Associations at Mikwan, Fenn and Chain Fields

The succession of facies associations and discontinuity surfaces in the study area is summarized in Table 4. Representative lithologs, along with core box photographs from each of the fields, illustrate the variable succession of facies associations in the study area. Three representative lithologs demonstrate the different possible successions of facies associations with examples from Mikwan, Fenn and Chain.

At Mikwan, a complete succession of FA1, FA2, FA3 and FA4, separated by their respective discontinuities occur (Figs. 29 and 30). In contrast, the litholog from Fenn demonstrates that erosion has removed FA2 and FA3 sits directly upon FA1 (Figs. 31 and 32). The litholog from Chain shows a situation where erosion has removed FA3 as well, and FA4 lies directly upon FA1 (Figs. 33, 34).

Downing and Walker (1988)	Pattison (1991)	Boreen and Walker (1991)	Study Area
FA 6-Black Mudstones	Lower Colorado Shales	FA E-Black mudstones, sandstones and conglomerates	Westgate Fm
No equivalent	No equivalent	No equivalent	Colorado Flooding Surface
No equivalent	No equivalent	No equivalent	FA5-Conglomerates
Bounding Surface E3	VE4	VE4	VE4
FA 5-Interlaminated sandstones and mudstones	FA 2-Dark mudstone	FA D-Silty sandstones, bioturbated mudstones and hummocky cross-stratified sandstones	FA4-Interbedded shales, sandstones and muddy sandstones
Bounding Surface CM5	VE3-5	VE3b	No equivalent
FA 4-Sandstones and Mudstones	FA 2-Dark mudstone	FA C-Mudstones, conglomerates and crossbedded sandstones	FA4-Interbedded shales, sandstones and muddy sandstones
Bounding Surface CM4	Not Mentioned	Not Mentioned	Discontinuity 1
FA 3-Cross-Stratified Sandstones pebbly mudstones, glauconitic, granular and pebbly sandstones	FA 6-Crossbedded sandstone	FA C-Mudstones, conglomerates and crossbedded sandstones	FA3-Cross-bedded sandstones
Bounding Surface E2	VE3-4	No equivalent	Discontinuity 2
FA 2-Bioturbated Sandstones	Not Mentioned	No equivalent	FA2-Pebbly sandstone
Bounding Surface E1	Not Mentioned	VE3a	Discontinuity 3
FA 1-Basal Siltstones	FA1-Bioturbated, coarsening upwards successions	Sandier upward successions	FA1-Regional Viking parasequences

Table 3-Comparison of the facies associations and bounding discontinuity nomenclature used by different authors for the Joffre, Gilby and Willesden Green fields and for this study.

Table 4-Compilation of erosional discontinuities and facies associations found in cored wells in the study area. Note that thicknesses of facies associations are not represented in this table.
Cored interval
Facies Association/Discontinuity removed by erosion

		Skolithos	*Thalassinoides*	*Diplocraterion*	*Arenicolites*	*Ophiomorpha*	*Rosselia*	*Teichichnus*	*Terebellina*	*Asterosoma*	*Subphyllochorda*	*Zoophycos*	*Rhizocorallium*	*Siphonichnus*	*Cylindrichnus*	*Schaubcylindrichnus*	*Palaeophycus*	*Planolites*	*Anconichnus*	*Chondrites*	*Helminthopsis*	*Lockeia*
FA 5	Facies 13	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Facies 6	○	○	○	x	○	x	◑	x	x	x	x	x	x	x	x	◑	x	x	x	x	x
FA 4	Facies 12	x	◑	◑	x	◑	◑	◑	x	◑	◑	◑	○	◑	○	x	●	x	●	◑	x	○
	Facies 11	○	x	○	x	○	○	◑	○	x	x	x	x	x	○	x	◑	◑	x	x	x	○
	Facies 6	○	○	○	x	x	x	◑	x	x	x	x	x	x	x	x	◑	x	x	x	x	x
FA 3	Facies 10	x	◑	◑	x	◑	x	●	x	●	x	x	x	x	x	x	●	x	x	x	x	x
	Facies 9	x	◑	x	x	◑	x	x	x	x	x	x	x	x	x	x	●	x	x	x	x	x
	Facies 8	◑	◑	◑	◑	○	x	x	x	x	x	x	x	x	x	x	◑	◑	x	x	x	x
	Facies 7	x	x	x	x	x	x	◑	○	x	x	x	x	x	x	x	x	◑	x	x	x	x
FA 2	Facies 5	◑	◑	x	◑	◑	●	x	◑	◑	●	●	x	x	x	x	●	●	◑	x	x	x
	Facies 4	x	○	x	○	x	x	●	x	x	x	x	x	◑	x	x	◑	●	○	x	x	x
	Facies 6	○	○	○	x	○	x	◑	x	x	x	x	x	x	x	x	◑	x	x	x	x	x
FA 1	Facies 3	x	x	○	x	◑	x	◑	◑	x	x	x	x	x	x	x	●	◑	●	x	x	x
	Facies 2	x	x	x	○	○	●	●	●	◑	◑	x	x	◑	x	◑	●	◑	●	◑	◑	x
	Facies 1	x	x	○	x	x	◑	●	◑	○	x	○	x	○	x	x	○	●	x	◑	●	x

Abundant ● Rare ○
Moderate ◑ Not observed x

Table 5-Relative abundance of ichnogenera within each facies association.

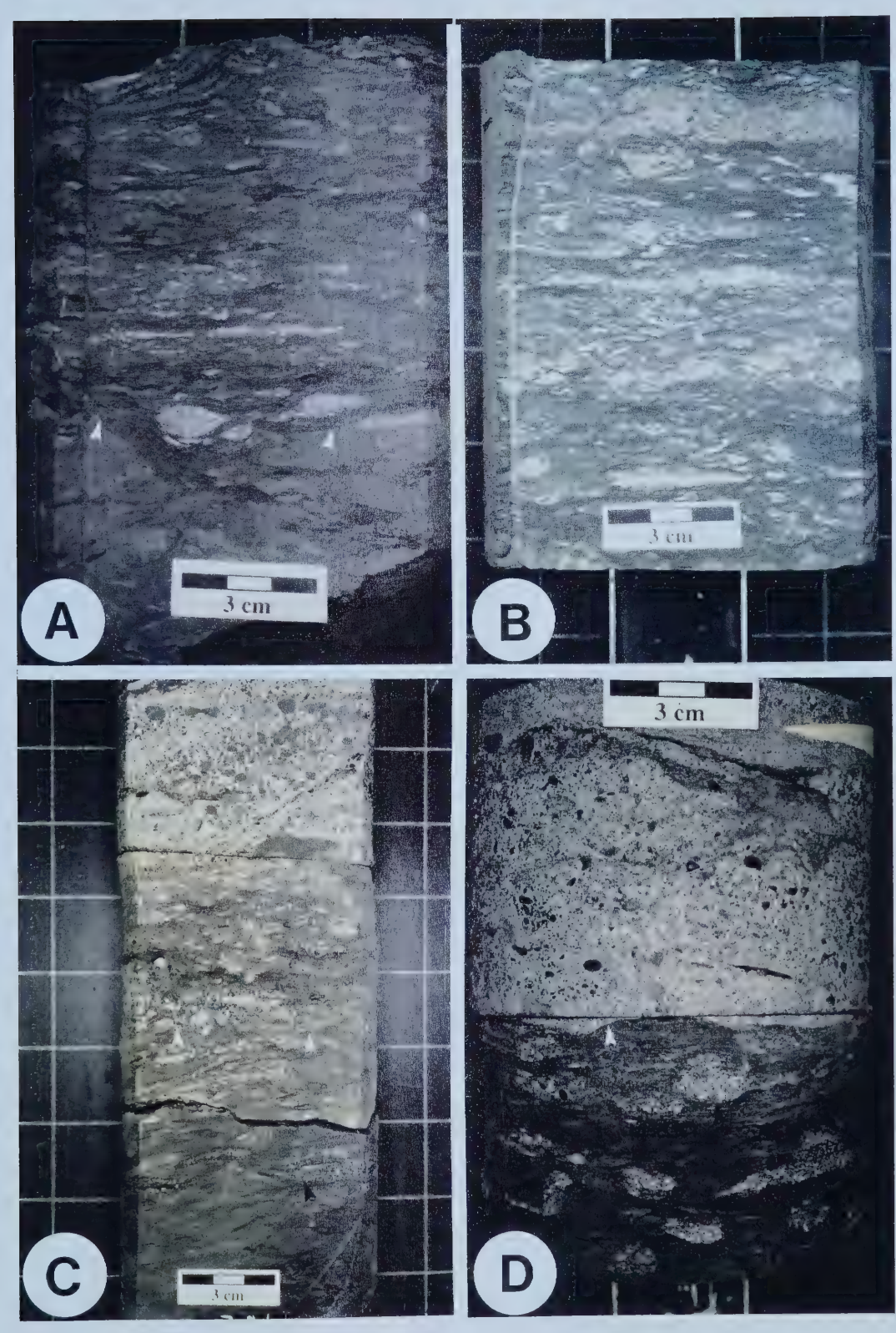
Figure 24 -Discontinuity 3:

(A) **7-20-37-23W4** Sharp contact (white arrows) between sandy shales of Facies 4 (FA2-pebbly facies association) and the underlying silty shales of Facies 1 (FA1-Regional Viking facies association). Depth 1388.5m.

(B) **14-18-34-18W4** Subtle contact between Facies 4 (facies association two-pebbly facies association) and the underlying sandy shales of Facies 1/2 (FA1-Regional Viking facies association). Contact here is not sharp, and is only demarcated by the presence of dispersed pebbles (white arrow). Depth 1145.7m.

(C) **4-32-36-21W4** Sharp contact (white arrows) between Facies 6 (FA2-pebbly sandstone facies association) and underlying silty shales of Facies 1 (FA1-Regional Viking facies association). Black arrow points to passively-infilled *Thalassinoides* network of the *Glossifungites* ichnofacies. Depth 1342m.

(D) **10-2-37-23W4** Sharp contact (white arrow) demarcated by the *Glossifungites* ichnofacies (black arrow) between Facies 5 (FA2-pebbly sandstone facies association) and underlying Facies 1 (FA1-Regional Viking facies association). Depth 1397m.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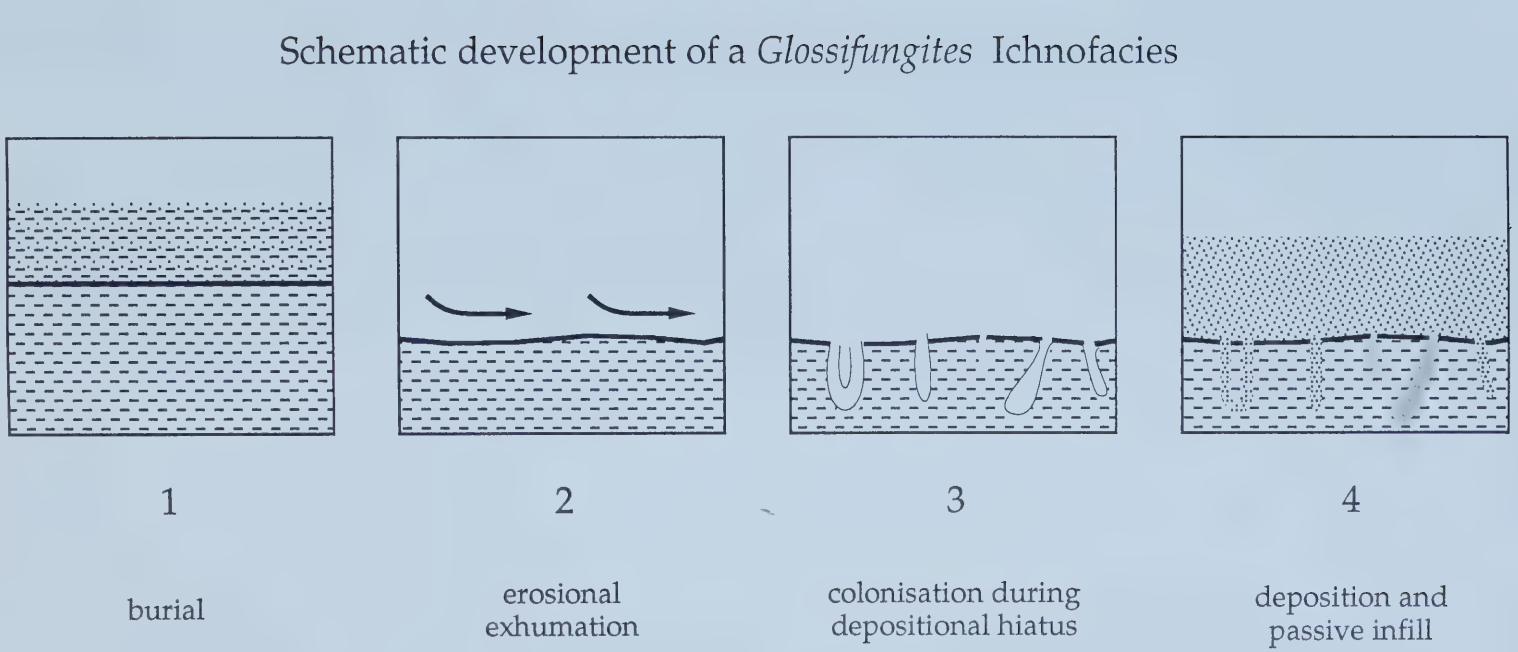

Figure 25. Schematic development of a *Glossifungites*-demarcated erosional discontinuity. 1) The muddy substrate is buried and dewatered, resulting in a compacted, stiff character. 2) The shaly bed is erosionally exhumed, exposing a firm substrate. 3) Colonisation of the discontinuity surface by tracemakers of the *Glossifungites* ichnofacies proceeds under marine conditions during a depositional hiatus. 4) The structures are passively filled during a succeeding depositional episode (modified after MacEachern *et al.*, 1992).

Figure 26-Discontinuity 2:

(A) **3-31-36-22W4.** Sharp contact between FA3 (cross-bedded facies association) and underlying FA2 (pebbly sandstone facies association), demarcated by sideritized rip-up clast (white arrow) and *Glossifungites* Ichnofacies. Depth 1403m.

(B) **3-18-37-23W4.** Sharp contact between Facies 9 (FA3 cross-bedded facies association) and the underlying sediments of the Facies 4/5 transition (FA2-pebbly sandstone facies association). Contact is demarcated by *Glossifungites* ichnofacies. Black arrows point to passively-infilled *Diplocraterion*. Depth 1376m.

(C) **11-13-34-20W4.** Contact (white arrow) between Facies 8 (FA3-cross-bedded facies association) and underlying deposits of Facies 2 (FA1-Regional Viking facies association). Depth 1235m.

(D) **7-29-36-23W4.** Sharp, *Glossifungites*-demarcated contact between Facies 8 (FA3-cross-bedded facies association) and the underlying Facies 2 (FA1-Regional Viking facies association). Depth 1461m.

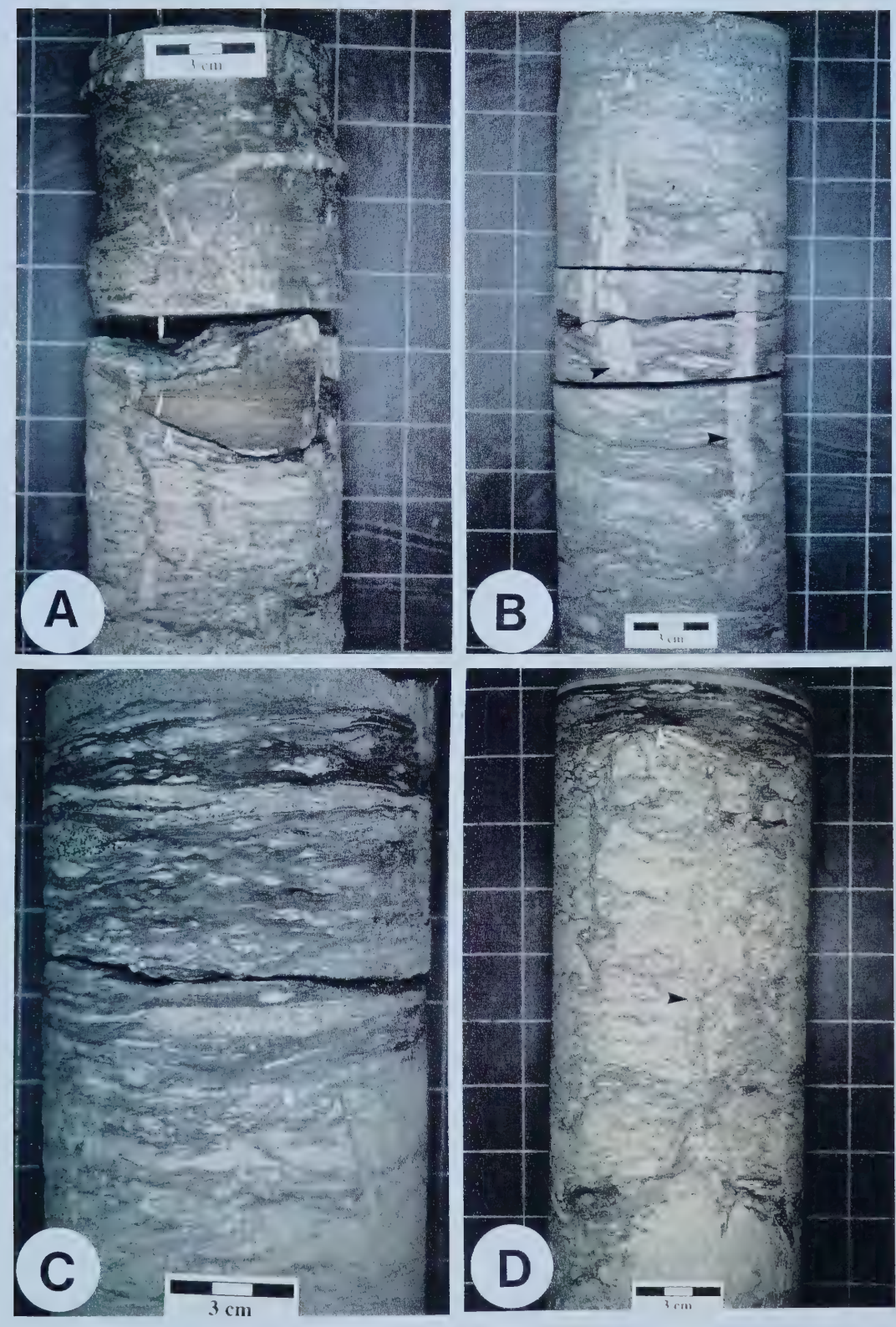
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Figure 27 -Discontinuity 1:

(A) **2-33-34-20W4**. Sharp contact with conglomeratic lag, (white arrow) between FA4 (interbedded shales and sandstone facies association) and underlying FA3 (cross-bedded facies association). Depth 1195m.

(B) **2-30-35-19W4.** Sharp contact (white arrow) between Facies 11 (FA4-interbedded shales and sandstone facies association) and underlying Facies 10 (FA3-cross-bedded facies association). Depth 1170m.

(C) **11-13-34-20W4.** Contact (white arrow) between FA4 (interbedded shales and sandstone facies association) and underlying Facies 8 (FA3-cross-bedded facies association). Depth 1226.7m.

(D) **10-3-32-17W4.** Contact (white arrow) between FA4 (interbedded shales and sandstone facies association) and FA3 (cross-bedded facies association). Note sideritized zone below contact. Depth 1081m.

A
3 cm
B
C
3 cm
D

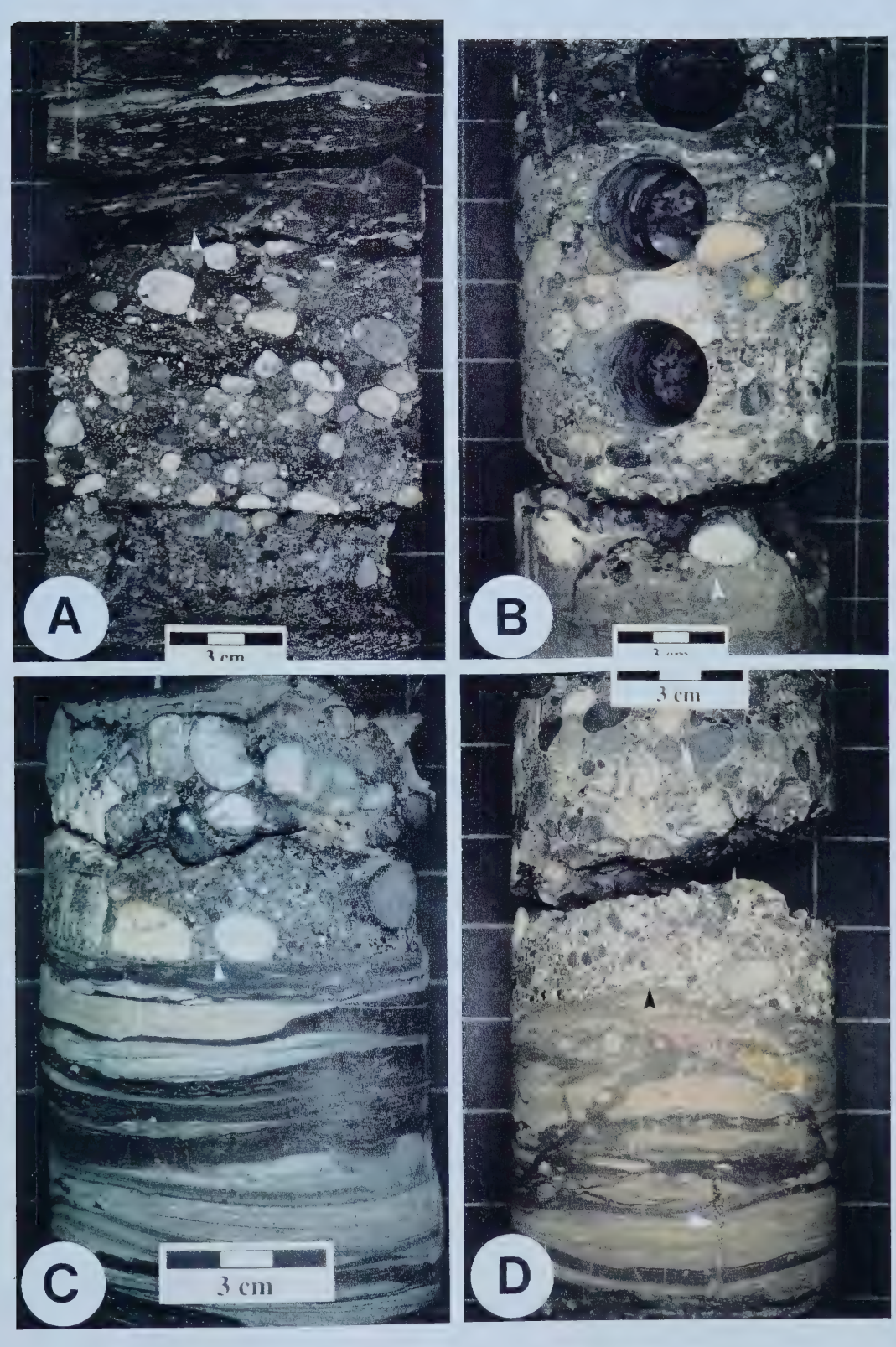
Figure 28-VE4 and the Colorado flooding surface:

(A) **8-1-36-22W4.** Contact between Westgate Fm (white arrow) and underlying FA5 (conglomerates pebbly sandstones and shale facies association). Depth 1282m.

(B) **8-1-36-22W4.** Sharp contact (white arrow) between FA5 (conglomerates pebbly sandstones and shale facies association) and underlying FA4 (interbedded shales and sandstone facies association). Depth 1282.4m.

(C) **11-6-33-20W4.** Sharp contact, demarcated by conglomeratic lag (black arrow) between FA5 (conglomerates pebbly sandstones and shale facies association) and underlying Facies 11 (FA4-interbedded shales and sandstone facies association). Depth 1195.2m.

(D) **7-1-37-24W4.** Sharp contact, demarcated by conglomeratic lag (black arrow) and *Glossifungites* ichnofacies (white arrow) between FA5 (conglomerates pebbly sandstones and shale facies association) and underlying Facies 12 (FA4-interbedded shales and sandstone facies association). Depth 1402m.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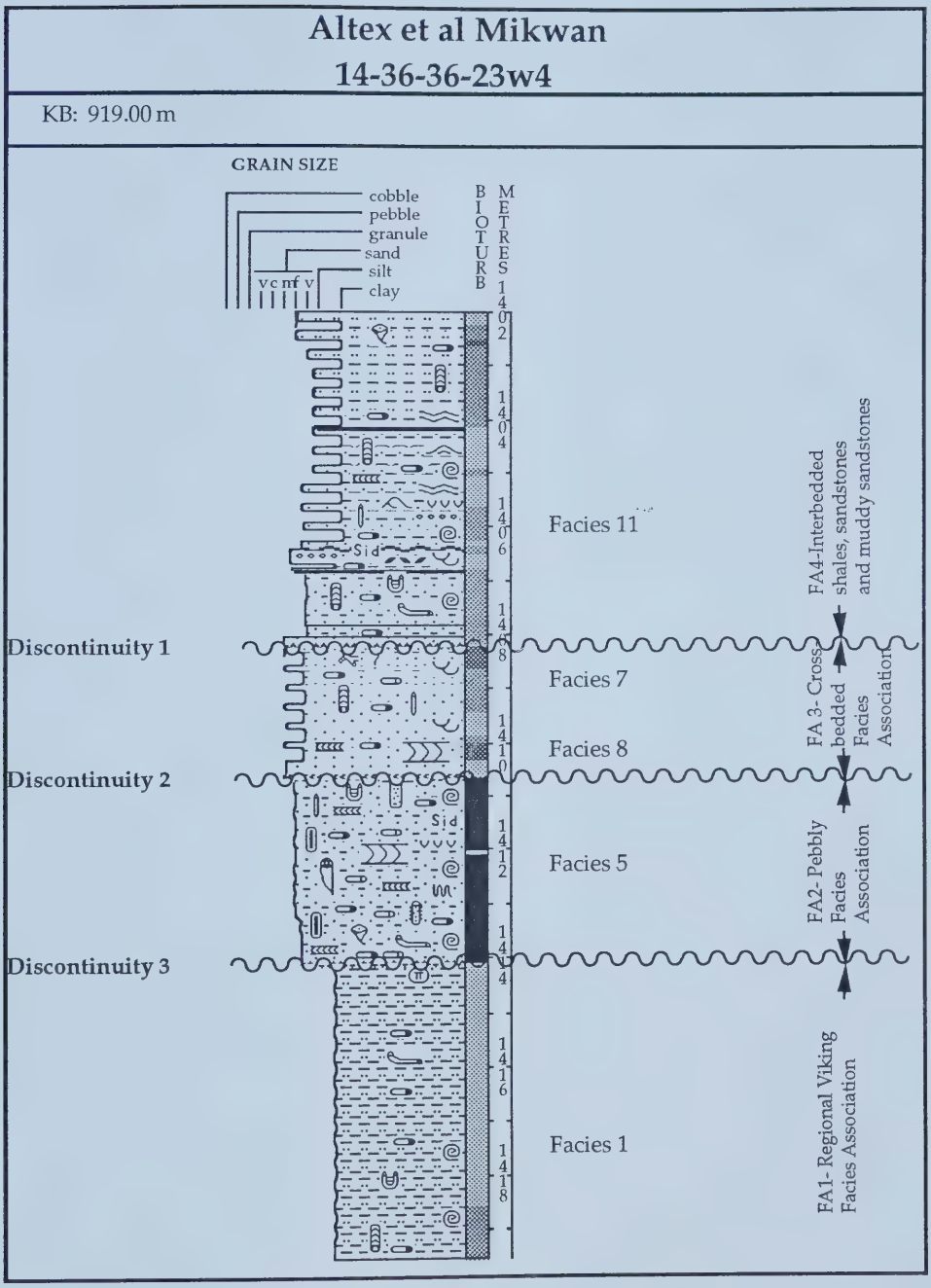
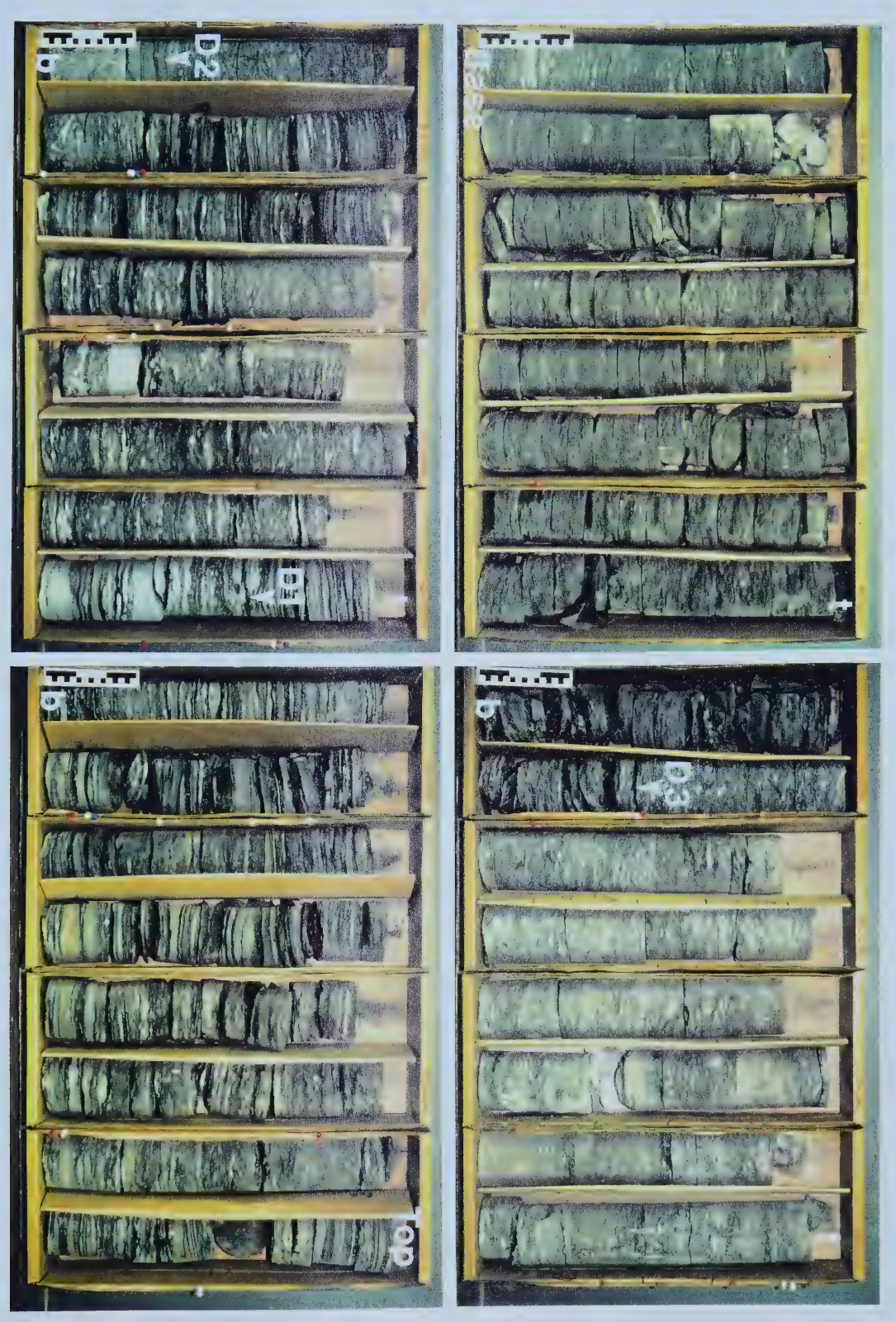


Figure 29- Example of a complete succession of facies associations. See litholog legend for explanation of symbols (Fig. 35).

Figure 30- Core Box Photographs of 14-36-36-23W4:
Core interval is 1402-1420m. Scale bar is 15cm in length. Base of core in top left photograph, top of core in bottom right photograph. Bottom of core (b), top of core (t). White arrows point to Discontinuity 3 (D3), Discontinuity 2 (D2) and Discontinuity 1 (D1) respectively.



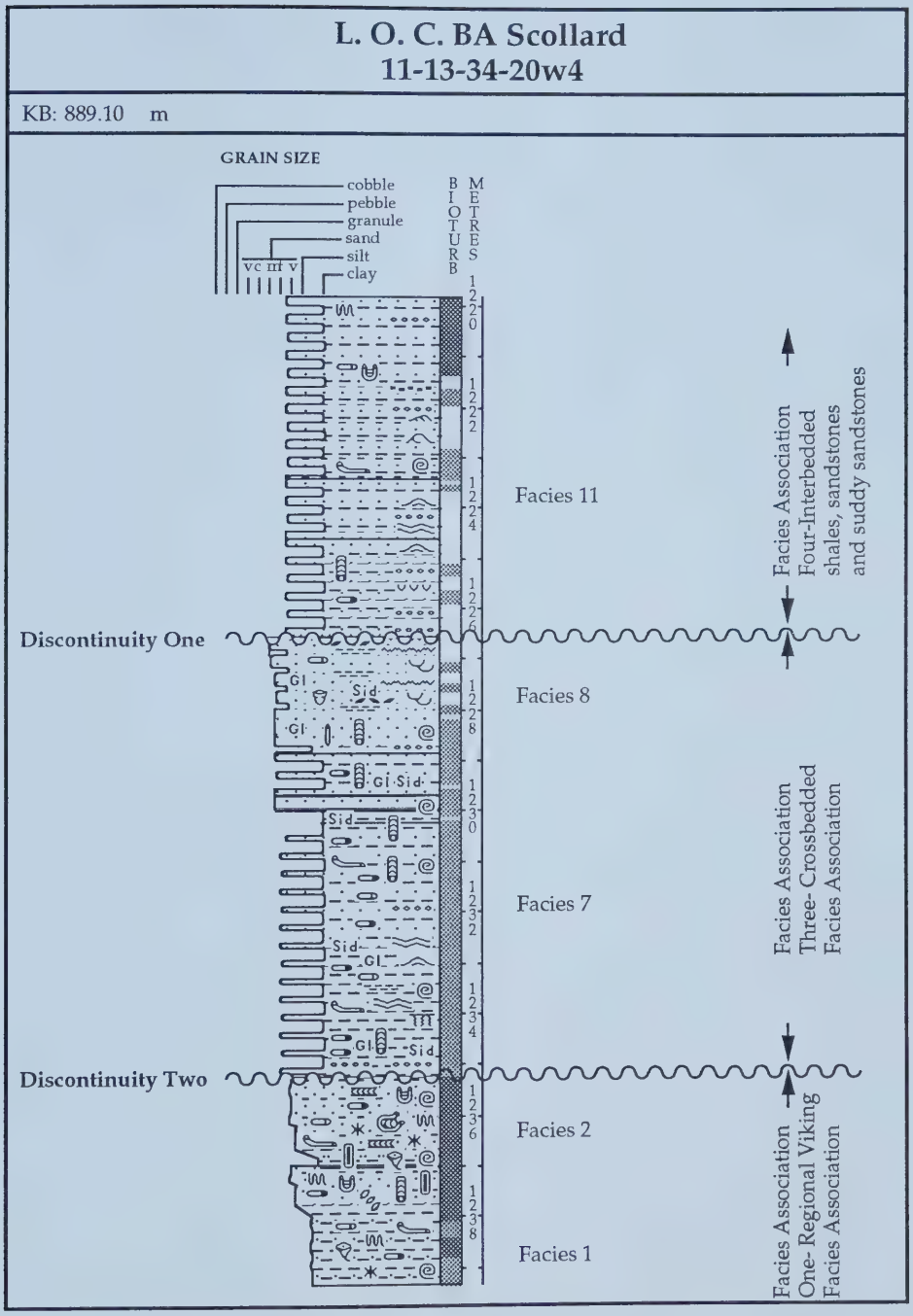
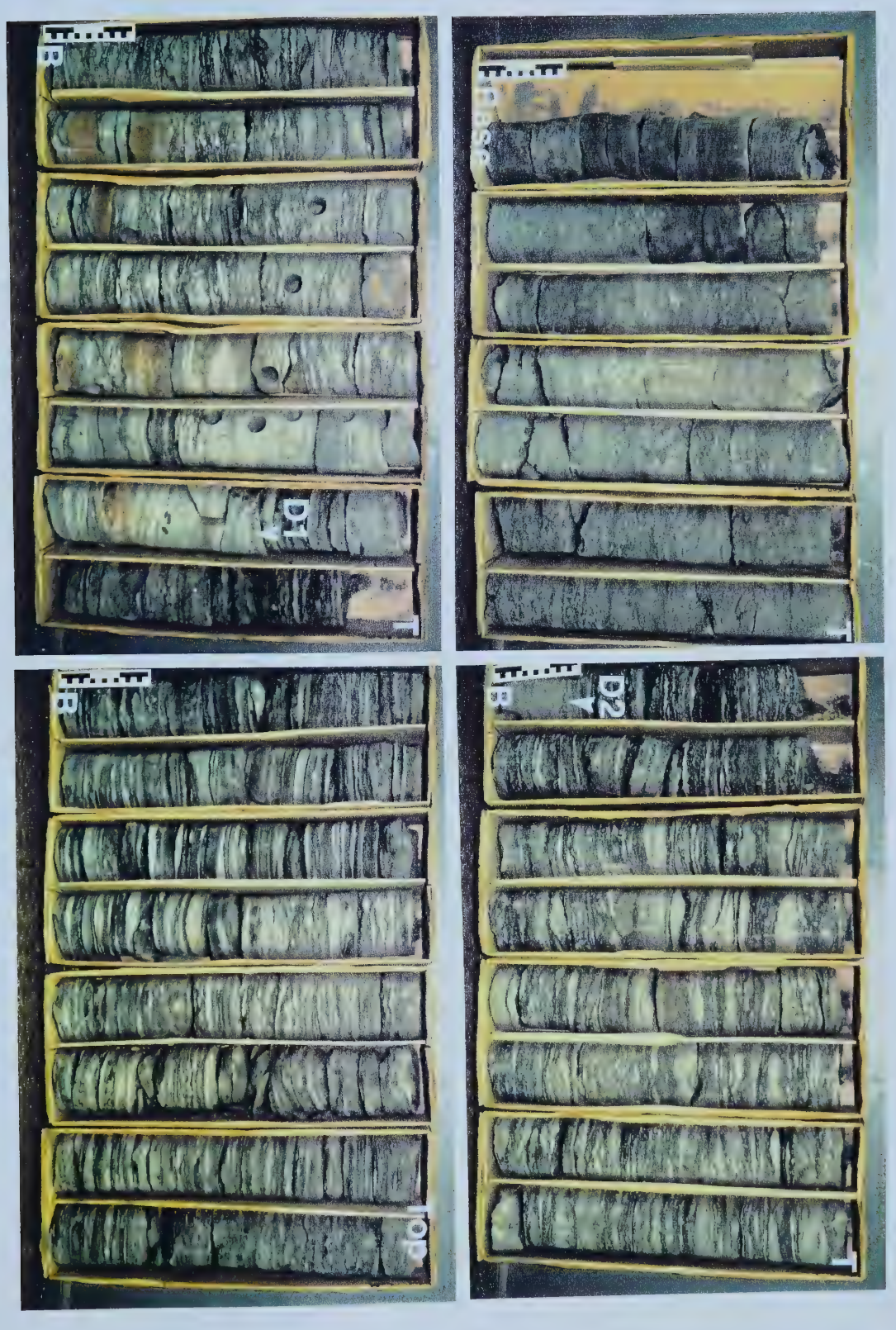


Figure 31-Succession of facies associations at Fenn Big Valley. Facies Association Two has been removed by erosion. See litholog legend for an explanation of symbols (Fig. 35).

Figure 32-Core box photographs of 11-13-34-20W4:
Core interval is 1220-1239m. Scale bar is 15cm in length. Base of core in top left photograph, top of core in bottom right photograph. Bottom of core (b), top of core (t). White arrows point to Discontinuity 2 (D2) and Discontinuity 1 (D1) respectively.


B
B1
T
B
B2
T
B
top
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B2
T

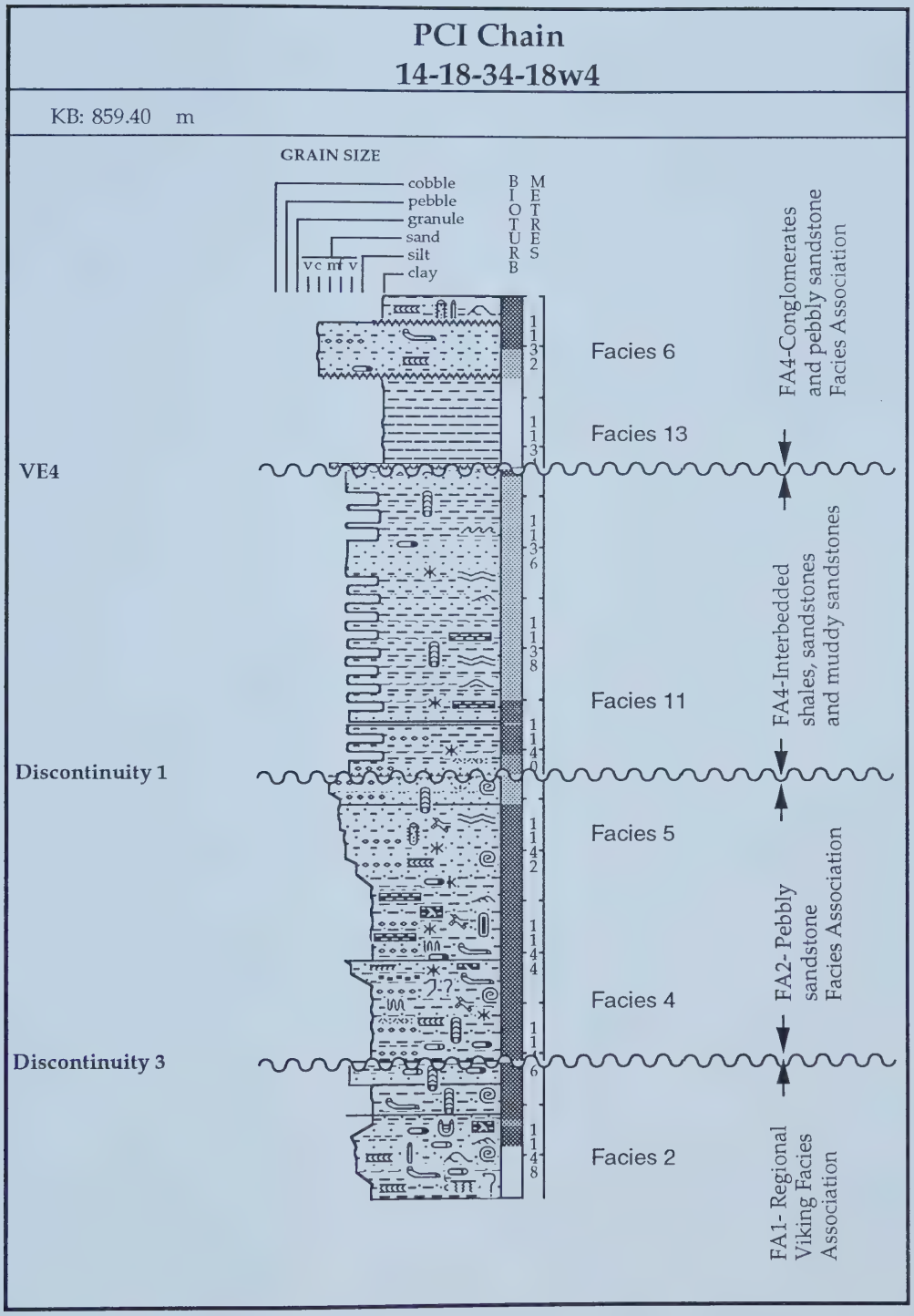
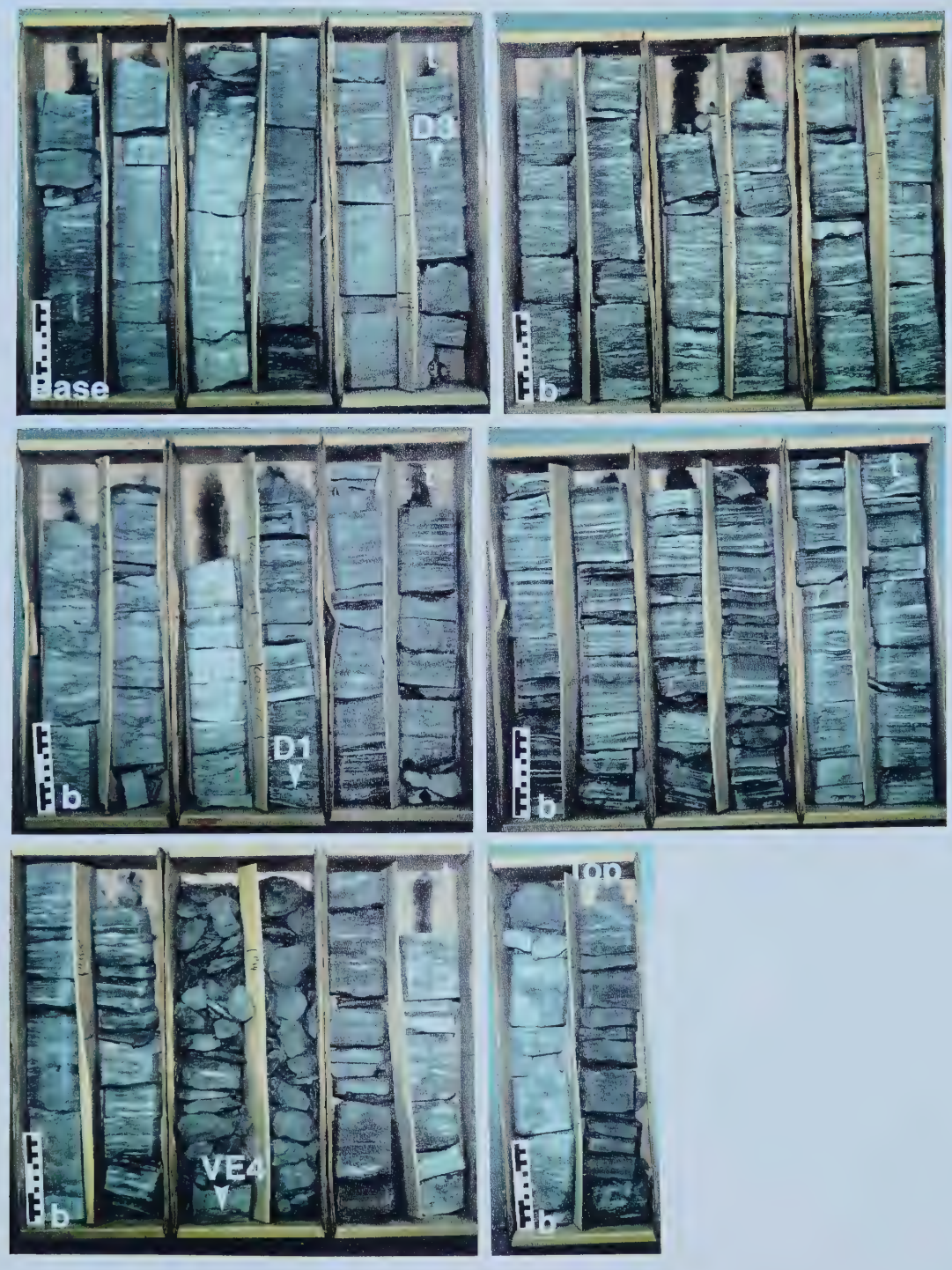


Figure 33- Succession of facies associations at Chain. FA3 has been removed by erosion. See litholog for an explanation of symbols.

Figure 34-Core box photographs of 14-18-34-18W4:
Core interval is 1131-1148m. Scale bar is 15cm in length. Base of core in top left photograph, top of core in bottom right photograph. Bottom of core (b), top of core (t). White arrows point to Discontinuity 3 (D3), Discontinuity 1 (D1) and VE4 respectively.


Base
D4
b
D1
b
b
VE4
b
OD
b

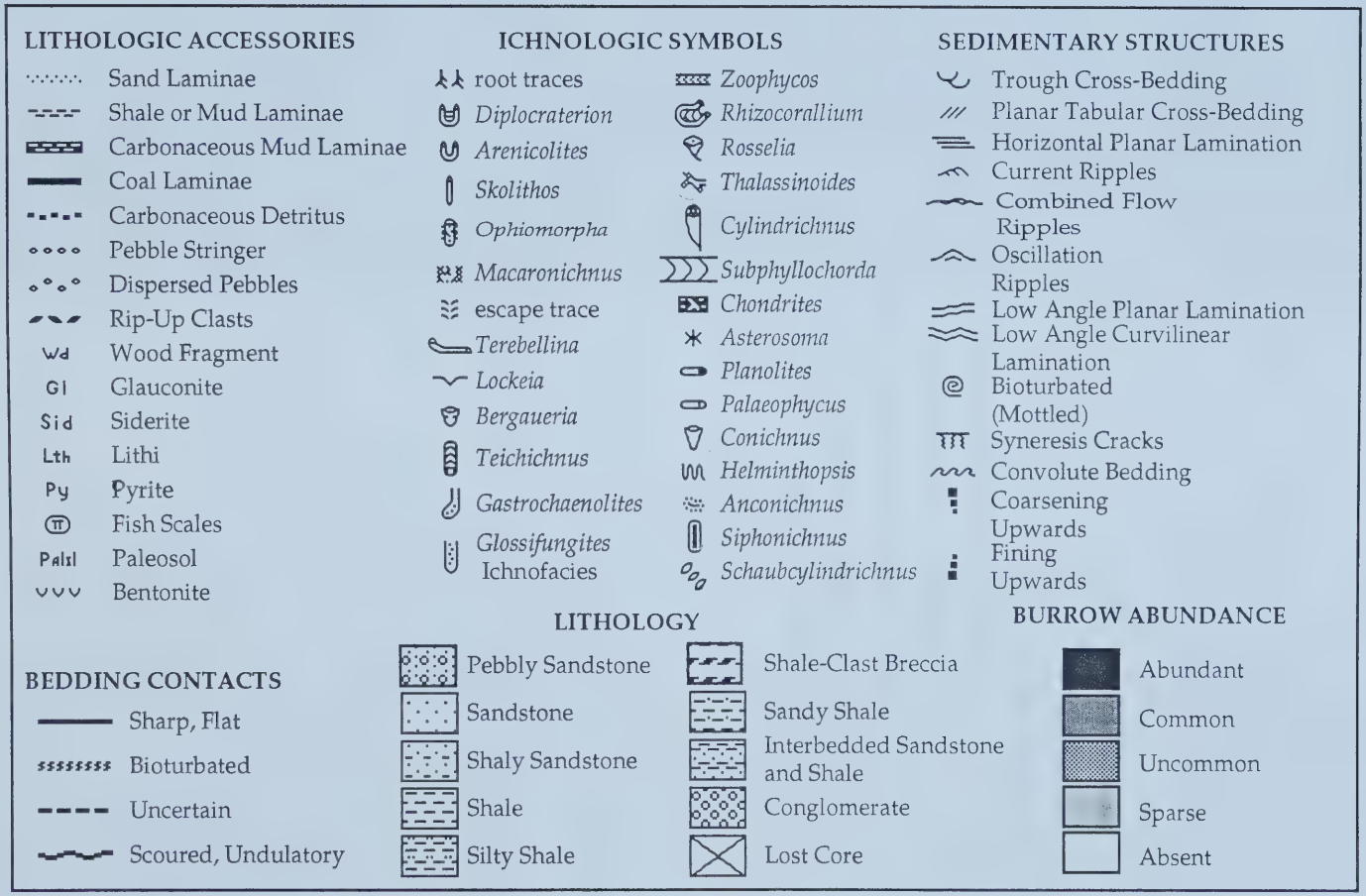


Figure 35- Legend of symbols used in lithologs.

CHAPTER FOUR: REGIONAL DISTRIBUTION OF FACIES ASSOCIATIONS AND DISCONTINUITY SURFACES

4.1: Introduction

The facies, facies associations and discontinuities been described in detail in the previous chapters. This chapter explains their lateral and vertical distributions in the study area. Cored wells, and their respective well logs, were used as templates to correlate facies associations and discontinuities in cross-sections and maps. Through the use of cross-sections and maps, a sense of both the vertical and lateral distributions of facies associations and discontinuities can be garnered. Each of these facies associations, with the exception of FA1, is bound by discontinuities that indicates that they are not genetically related to either underlying, or overlying facies associations. As a result, Walther's Law applies to facies successions within each facies association, but not between facies associations. In fact, each of the facies associations can be considered to be an allomember of the Viking alloformation.

4.2: Allostratigraphy

Allostratigraphy is recognized by the North American Commission on Stratigraphic Nomenclature (NACSN, 1983)) which defines an allostratigraphic unit as "a mappable stratiform body of sedimentary rock that is defined and identified on the basis of its bounding discontinuities". In contrast, sequence stratigraphy is based on the recognition of the sequence, which is bound by lowstand unconformities or correlative conformities and composed of genetically-related depositional systems, or system tracts (van Van Wagoner, *et al.*, 1990). Each system tract is then in turn defined on the basis of its position within the sequence, the types of bounding surfaces and by its parasequence set distribution (Van Wagoner, *et al.*, 1990). While sequence stratigraphy has proven to be both a powerful interpretative and descriptive tool for stratigraphers, it does have the following inherent shortcomings when compared with allostratigraphy: 1) sequence stratigraphy emphasizes lowstand surfaces of erosion and downplays those surfaces cut during transgressive ravinement, while allostratigraphy gives equal weight to all

bounding discontinuities (Pattison, 1991) and 2) the genesis of erosional surfaces in sequence stratigraphy is implicit in their definition while in allostratigraphy bounding discontinuities do not have an implicit definition (Walker, 1992). Different interpretations as to the genesis of an interval's discontinuities lead to markedly different stratigraphic models for the succession. Perhaps the main strength of allostratigraphy is that new interpretations pertaining to the formation of allomembers and bounding discontinuities can arise, or evolve over time, without changing the fundamental identification of the bounding discontinuities or allomembers.

Allostratigraphy can be used to subdivide the Viking Formation into allomembers, bounded by discontinuities, and allows the practical subsurface mapping and correlation of the Viking Formation. The Viking Alloformation has been informally defined and subdivided into allomembers (Fig. 36), extending from the first major rightward inflection on resistivity logs above the top of the Mannville Group to the Base of Fish Scales Marker (Boreen and Walker, 1991). Allostratigraphic concepts have been applied by several workers in their studies of the Viking Fm, proving it to be a useful tool which has helped to subdivide the Viking Fm into practical, correlatable units (Boreen, 1989; Hadley, 1992; Pattison, 1991, Wiseman, 1994). Using allostratigraphic concepts, erosional discontinuities (bounding surfaces) within the Viking Formation, along with the sedimentary units bounded by these surfaces, can be correlated. The sedimentary units, or allomembers, correlated in this manner are therefore more likely to be genetically equivalent, even though they may have differing lithologies.

In this study, FA2, FA3, FA4 and FA5, which are bound by discontinuities, can be defined as allomembers. To avoid the confusion that would be caused by renaming these facies associations as new allomembers, their names will remain unchanged. For the study area, cross-sections were constructed to both correlate facies associations and to demonstrate their vertical and spatial relationships in the study area.

4.3: Cross-sections

Four representative cross-sections (Fig. 37) were constructed to display the vertical relationships of facies associations in the study area. Where possible, cross-sections were constructed with paired gamma ray and

resistivity logs, with the gamma ray log on the left track. Cored intervals in wells are indicated by a vertical black bar extending through the appropriate interval. All scales on well logs are in metres.

A prominent bentonite marker, Log Marker Two, (LM2) was observed in FA1 (Regional Viking Facies Association) and was used as the stratigraphic datum. In well logs, LM2 forms a distinctive double bump or peak on both resistivity and a right hand deflection on gamma ray logs. The marker, LM2, was chosen as a datum for the following reasons: 1) it has proven to be regionally extensive in the study area and beyond, 2) it forms a prominent well log marker that is easily picked on well logs, and 3) it is found in sediments of offshore origin and therefore serves as a proxy for the slope of the offshore. Such a slope can be regarded as flat lying, with little topographic relief. While the Base of Fish Scales Marker has been traditionally used as a stratigraphic datum for the Viking Formation, it did not prove to be a good datum for the detailed cross-sections used in this study. Other possible datums exist in the shales of the Westgate Fm and the Joli Fou Fm, but have proven difficult to pick with any sense of consistency in the study area.

Immediately above the LM2 datum, another marker, designated as Log Marker One (LM1) was also correlated. Like LM2, LM1 is a bentonitic horizon within FA1, probably deposited as a flat-lying horizontal bed, and is found throughout the study area, except where it has been removed by erosion. The LM2 and LM1 markers are essentially sub-parallel to one another throughout the study area supporting their appropriateness as a datum. The markers LM2 and LM1 have also been observed at the Joffre field, to the northwest (Downing, 1986). The top of the Mannville Group and the Base of Fish Scales Marker were also correlated on the cross-sections along with the discontinuities.

4.3.1: Cross-section A-A'

Cross-section A-A' is located in the northwest corner of the study area and is constructed perpendicular to the strike of the Mikwan field (Fig. 37). Several cored wells in the Mikwan field enabled the discontinuities and facies associations to be correlated with a high degree of accuracy. One of the obvious features of Cross-section A-A' (Fig. 38) is the thinning of the Viking Fm in a basinward (northeast) direction as well as the progressive removal of the regional Viking Fm parasequences (FA1) in the same direction. This

cross-section also gives strong evidence that the discontinuities are erosional surfaces.

Discontinuity 3, which is the stratigraphically lowest discontinuity, appears to be an erosive surface for the following reasons: 1) it cuts stratigraphically down towards the LM1 marker in Cross-section A-A'; 2) it is commonly demarcated by the *Glossifungites* ichnofacies in drill core, which is evidence of an erosional discontinuity; 3) it is commonly mantled above by a conglomeratic lag, and 4) a sharp lithologic change occurs between FA2 and FA1. The preserved "nick-point" or the point where the incision of Discontinuity 3 starts, occurs between the 7-20-36-23W4 and 7-1-37-24W4 wells. Southwest of this point, Discontinuity 3 and overlying FA2 has been removed by Discontinuity 2.

Discontinuity 2 is also interpreted to be an erosional surface, since it too cuts stratigraphically downward in a basinward direction removing underlying deposits of FA2. Though Discontinuity 2 is not commonly demarcated by the *Glossifungites* Ichnofacies, where it does occur in drill core, it shows evidence of an erosional discontinuity. The surface is characterized by a sharp lithologic, sedimentologic and ichnologic change between FA2 and FA3, indicating that these facies associations are not genetically related. The overlying sediments of FA3 persist in a landward (southwest) direction, farther than those of FA2 which indicates that the "nick-point" for Discontinuity 2 is itself further landward than that of Discontinuity 3, possibly between the 15-14-35-24W4 and the 10-7-36-23W4 wells.

Discontinuity 1 appears to a be an low energy flooding surface seaward , but becomes erosional landward rising stratigraphically, in a stepwise fashion, to the southwest. Evidence of erosion for Discontinuity 1 is supplied by the conglomeratic lags that immediately overlie this surface. The *Glossifungites* ichnofacies was only rarely observed, possibly indicating that this was a rapid flooding event which did not allow the colonization of the exhumed substrate. Other evidence for erosion is offered by the removal of Discontinuity 2 and FA3 in a landward direction. Unlike Discontinuities Two and Three, Discontinuity 1 persists throughout this cross-section, separating the sediments of the regional Viking parasequences, FA1, in the southwest and FA2 in the northeast, from the overlying interbedded shales of FA4. FA4 clearly thickens in a landward direction.

Bounding the top of FA4 is the regionally extensive, Viking Erosion Surface Four (VE4). Like Discontinuity 1, VE4 rises stratigraphically in a stepwise manner to the southeast. It also appears to be an erosional discontinuity, removing the underlying bentonite bed (sharp right-ward gamma ray deflection on well logs) in a basinward direction (between 7-20-36-23W4 and 14-12-37-24W4). The erosional surface VE4 is commonly demarcated by the *Glossifungites* ichnofacies and is typically mantled by a conglomeratic lag. The overlying deposits of FA5 thin in a basinward direction, and thicken in a landward direction.

The last discontinuity in Cross-section A-A' is the flooding surface which marks the start of deposition of the marine shales of the Westgate Fm. This flooding surface is sharp and is commonly highlighted by a pebble lag or conglomeratic layer. The Colorado Shale flooding surface is sub- parallel to the underlying VE4 surface and corresponds to the top of the Viking Fm.

4.3.2: Cross-section B-B'

Cross-section B-B' (Fig. 39) is constructed perpendicular to the orientation of the Fenn West field, immediately to the southeast of Cross-section A-A' (Fig. 37). Since the vertical stacking arrangements of facies associations and the relationships of discontinuities has been described in detail for Cross-section A-A', only details unique to Cross-section B-B' will be pointed out. The "nick-point" where Discontinuity 3 stratigraphically incises into the underlying FA1 occurs between wells 8-1-36-22W4 and 7-18-36-21W4. Here, Discontinuity 3 has abruptly removed the regional marker LM1. Further basinward, Discontinuity 3 continues to downcut until it almost rests directly upon LM2.

Discontinuity 2 has removed any evidence of Discontinuity 3 and FA2 southwest of the 7-18-36-21W4 well and is in turn removed by Discontinuity 1, southwest of the 6-21-35-22W4 well. Discontinuity 2 also sharply incises into the underlying sediments of FA2, northeast of the 7-18-36-21W4 well and likely removes FA2 entirely further basinward. This is however, difficult to determine with any certainty due to several factors: 1) the lack of core control basinward, 2) the "shaling-out" and amalgamation of facies associations on well logs in a basinward direction, and 3) the likelihood that discontinuities basinward are more likely to be correlative conformities, or at least erosional.

All of the above factors have combined to make the recognition of discontinuities in a basinward direction extremely difficult.

4.3.3: Cross-section C-C'

Cross-section C-C' (Fig. 40) is located southeast of Cross-section B-B' and is constructed perpendicular to the strike of the Fenn Big Valley field (Fig. 37). While the succession and distribution of facies associations is similar to that of the preceding cross-sections, there are some important differences.

One of the prominent differences in Cross-section C-C' is the thick accumulations of FA3 which persists, unlike the previous two cross-sections, in a landward direction. In Cross-sections A-A' and B-B', Discontinuity 1 has removed most of FA3 in a landward direction with only a thin, (1 to 2 m thick) layer preserved. In Cross-section C-C', the thickness of FA3 persists and only thins just before it is removed entirely between the 14-23-33-21W4 and 3-7-34-20W4 wells. The thickness of FA3 is likely controlled by Discontinuity 1, which appears to have risen, in a stratigraphic sense, between the 8-2-35-20W4 and the 2-33-34-20W4 wells. This rise in turn allows for the preservation of a greater thickness of FA3. Another control on the thickness of FA3 is the morphology of the underlying Discontinuity 2 surface, which controls the accommodation space available for FA3. Discontinuity 2 also rises stratigraphically in a stepwise manner, similar to that of Discontinuity 1. All of these factors act in concert to control and enhance the preserved thickness and distribution of FA3 in Cross-section C-C' and explain the changes in thickness of FA3 from "thick to thin to thick", from a basinward to landward direction.

FA5 and VE4 also display some interesting features in this cross-section. In the 8-2-35-20W4 well, FA5 thickens appreciably and may contain an additional erosional discontinuity, lying above VE4. This erosional discontinuity lies immediately above a thick shale layer (the sharp right-ward deflection on the gamma ray log), separating the shale layer from the overlying pebbly sandstones and conglomerates. This surface appears to have incised and ultimately amalgamated with the underlying VE4 surface. If this is the case, it appears that there is at least one additional erosional surface within FA5. This surface may constitute the true VE4 surface, and the underlying erosional surface in the 8-2 well, labeled VE4 on the cross-section, may actually reflect a remnant, stratigraphically older erosion surface.

4.3.4: Cross-section D-D'

The final cross-section in the study area is located to the southeast of Cross-section C-C' and is constructed perpendicular to the strike of the Chain field (Fig. 37). Cross-section D-D' (Fig. 41) differs noticeably from the other cross-sections in that Discontinuity 1 has removed all evidence of FA3 and Discontinuity 2 from wells 10-5-34-18W4 to 14-18-34-18W4 in the vicinity of the Chain field.

In Cross-section D-D', instead of the thinning trend displayed by FA3 in Cross-section C-C', there is complete removal of FA3. The removal of FA3 in Cross-section D-D' may be the result of two factors, which were noticeable to a lesser degree in Cross-section C-C' (Fig. 40). In Cross-section C-C', FA3 "thins" in the 8-2-35-20W4 well immediately to the southwest of a rise in the underlying Discontinuity 2 surface, since the overlying Discontinuity 1 surface does not rise till a point southwest of the 8-2 well.

In Cross-section D-D'(Fig. 41) this situation is even more pronounced. Here Discontinuity 2 stratigraphically rises in "stepwise" fashion from the 16-31-34-18W4 to the 6-20-34-18W4 wells. The overlying Discontinuity 1 surface, however does not rise stratigraphically until considerably southwest of this point, between the 10-5-34-18W4 and 4-32-33-18W4 wells. As a result, FA3 thins, similar to Cross-section C-C', but without a concomitant rise in Discontinuity 1, FA3 is removed, until Discontinuity 1 rises immediately southwest of 10-5-34-18W4. The rapid stratigraphic rise of Discontinuity 2 also explains the widespread preservation of the underlying sediments of FA2.

4.3.5: Summary of features observed in cross-sections

After examining the above cross-sections it is apparent that some general observations about the distribution, and nature of, facies associations and discontinuities can be made. Of the common features displayed by the above cross-sections, the most important are: 1) the abrupt stratigraphic downcutting by Discontinuities 2 and 3 which results in a bevel or asymmetrical incision, 2) the amalgamation and removal of underlying erosional discontinuities by Discontinuity 1 in a landward direction, 3) the thick to thin to thick distribution of FA3 which is controlled by the relative

changes in morphology of Discontinuities 2 and 1, VE4) and the distribution of FA4 and FA5 throughout the study area.

4.4: Maps

Using the cross-sections as a guide, more than 470 well log suites were examined, and correlated. The resulting information was used to produce isopach maps of measured intervals. Isopach maps for FA2, FA3, FA4 and FA5 were constructed, in addition to isopach maps of the interval from the LM2 marker to Discontinuities 1, 2 and 3. No isopach map for FA1 was constructed as it serves as the platform on which FA2-FA5 lie. The isopach maps of LM2 to the discontinuities illustrate the significant changes in FA1 thickness. The facies association isopach maps help to illustrate both the zero edge and thickness variations of the facies associations, while the isopachs from LM2 to the discontinuities show the relief or paleotopography of the discontinuity surfaces. As previously mentioned, it proved extremely difficult to correlate facies associations in the northeast section of the study area with any degree of certainty, due to the "shaling-out" of facies associations and the overall lack of core control.

4.4.1: Isopach map of FA2

This isopach map illustrates the regional distribution of FA2, which is bound at its base by Discontinuity 3 and at its top by Discontinuity 2 (Fig. 42). The erosional edge of FA2 is defined in a landward direction by the zero isopach, showing where FA2 was removed by overlying Discontinuity 2 (Fig. 42). The zero edge of FA2 does not form a straight line, but in fact, bulges in the middle of the study area where it has been removed by the overlying Discontinuity 2. In a basinward direction, the isopach trend is uncertain but it appears to demonstrate a thinning trend and may, in fact, be removed by Discontinuity 2. FA2 ranges in thickness from 0-7 m, and is thickest in the vicinity of the Chain field.

4.4.2: Isopach map of FA3

FA3 is bound at its base and top by Discontinuities Two and One, respectively. In comparison with the isopach map of FA2 (Fig. 42), it is evident that FA3 extends further landward to the southwest (Fig. 43). The

zero edge of FA3 while not a straight line, trends northwest to southeast with one prominent bulge in T35, R22 to T35, R21W4, where it has been removed by Discontinuity 1.

FA3 displays a "thickening to thinning to thickening" trend of its isopachs in a landward to basinward direction, defining two separate trends of elongate, thicker deposits of FA3. In between these thicker developments, FA3 dramatically thins and, in the vicinity of the Chain field, has been removed entirely (Figs. 41, 43). FA3 varies in thickness from 0-11 m.

4.4.3: Isopach map of FA4

FA4 is bound at the base by Discontinuity 1 and at the top by VE4. FA4 is found distributed throughout the study area with the thickest isopachs in the southeast of the study area (Fig. 44). While the general strike of the 10 and 5 metre contour lines follows the trend of previous maps, the 15 and 20 metre contour does not. As in previous isopach maps, FA4 thins in a basinward (northeast) direction.

4.4.4: Isopach map of FA5

FA5 is bounded at the base by VE4 and at the top by a major flooding surface, overlain by the marine shales of the Westgate Fm. FA5 is distributed throughout the study area and appears to thin to the northwest and in a basinward (northeast) direction (Fig. 45). The thickness of FA5 varies from 0.6 to 6 m. FA5 lacks predictable trends in the study area.

4.4.5: Isopach map of interval from LM2 to Discontinuity 3

With the assumption that LM2 was a horizontal datum at the time of Discontinuity 3 incision, this isopach map demonstrates the relief, and to a certain degree, the morphology, of the Discontinuity 3 erosional surface. Thicks represent paleotopographic highs while thins reflect deeper incision. The close spacing of the five and ten metre contour lines (Fig. 46) illustrates the abrupt incision by Discontinuity 3 in this area, which has formed a beveled surface, in which thicker accumulations of FA2 have accumulated (Fig. 42). Further basinward (northeast) of the trend of the five and ten metre contour lines, the slope of the Discontinuity 3 surface appears to have decreased, until it eventually removes the LM2 marker.

4.4.6: Isopach map of interval from LM2 to Discontinuity 2

Like the isopach from LM2 to Discontinuity 3, this map serves as a paleotopographic map of Discontinuity 2. The contour lines of this map (Fig. 47) display an overall northwest-southeast trend, similar to the contour trend for the previous map of Discontinuity 3 (Fig. 46). The ten and five metre contour lines are spaced slightly closer together and indicate that the Discontinuity 2 erosional surface is beveled, or asymmetrical. It is not as abrupt as the beveling of the Discontinuity 3 surface in the previous map (Fig. 46) however. In the vicinity of the Chain field the Discontinuity 2 surface has been removed by the overlying Discontinuity 1 surface, represented on the map by a zero isopach.

4.4.6: Isopach map of interval from LM2 to Discontinuity 1

The last isopach map displays the morphology of the Discontinuity 1 surface (Fig. 48). As in the previous two maps, the contour trend is from northwest to southeast. The dip of the Discontinuity 1 surface appears to be gradual without bevels or abrupt incision of the erosional discontinuity. In no localities has it been removed by VE4. There are several localized exceptions to this generalization, but it is clear that unlike Discontinuity 3, there is no evidence of a beveling or abrupt incision for the Discontinuity 1 surface, and it simply rises stratigraphically landward to the southwest.

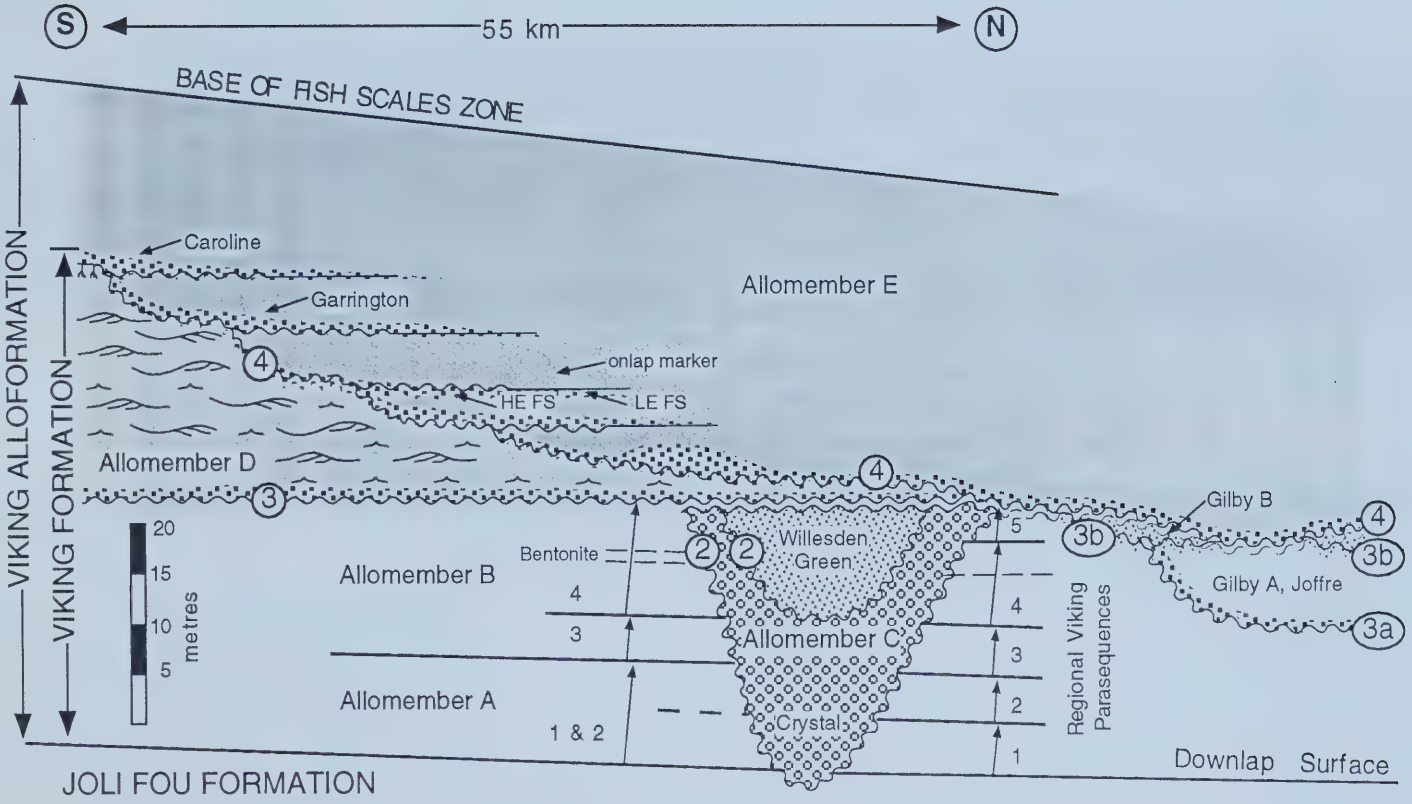


Figure 36- Allostratigraphic framework proposed for the Viking Formation. The Viking Alloformation contains 5 Allomembers (A-E), separated from one another by regional discontinuities. The main discontinuities are VE2 (2), VE3 (3) and VE4 (4), with secondary erosion surfaces present as well. Study area is equivalent to Gilby A and Joffre areas. Figure modified after Boreen and Walker (1991).

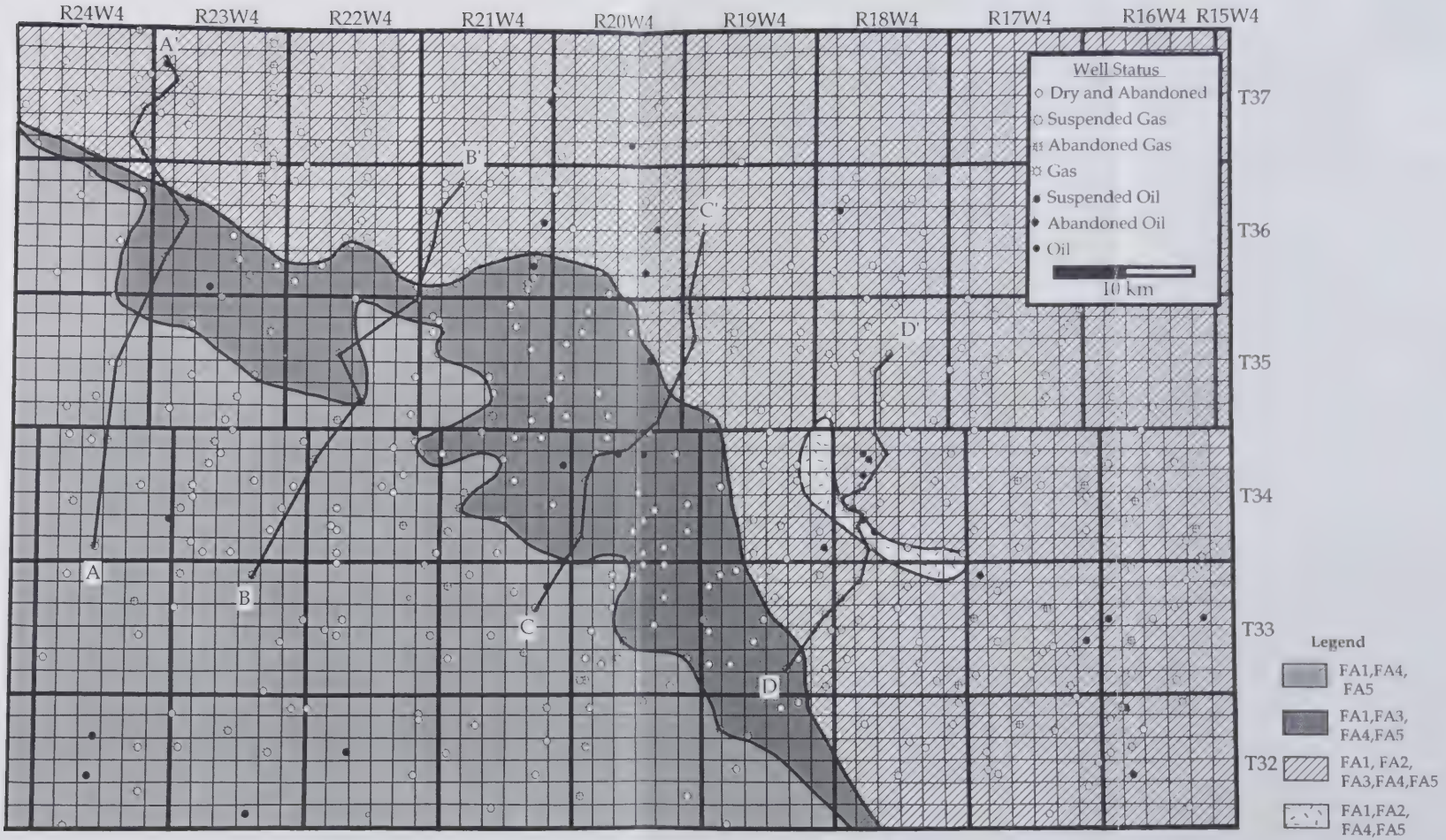


Figure 37-Facies Associations (FA) distribution map and location of cross-sections.

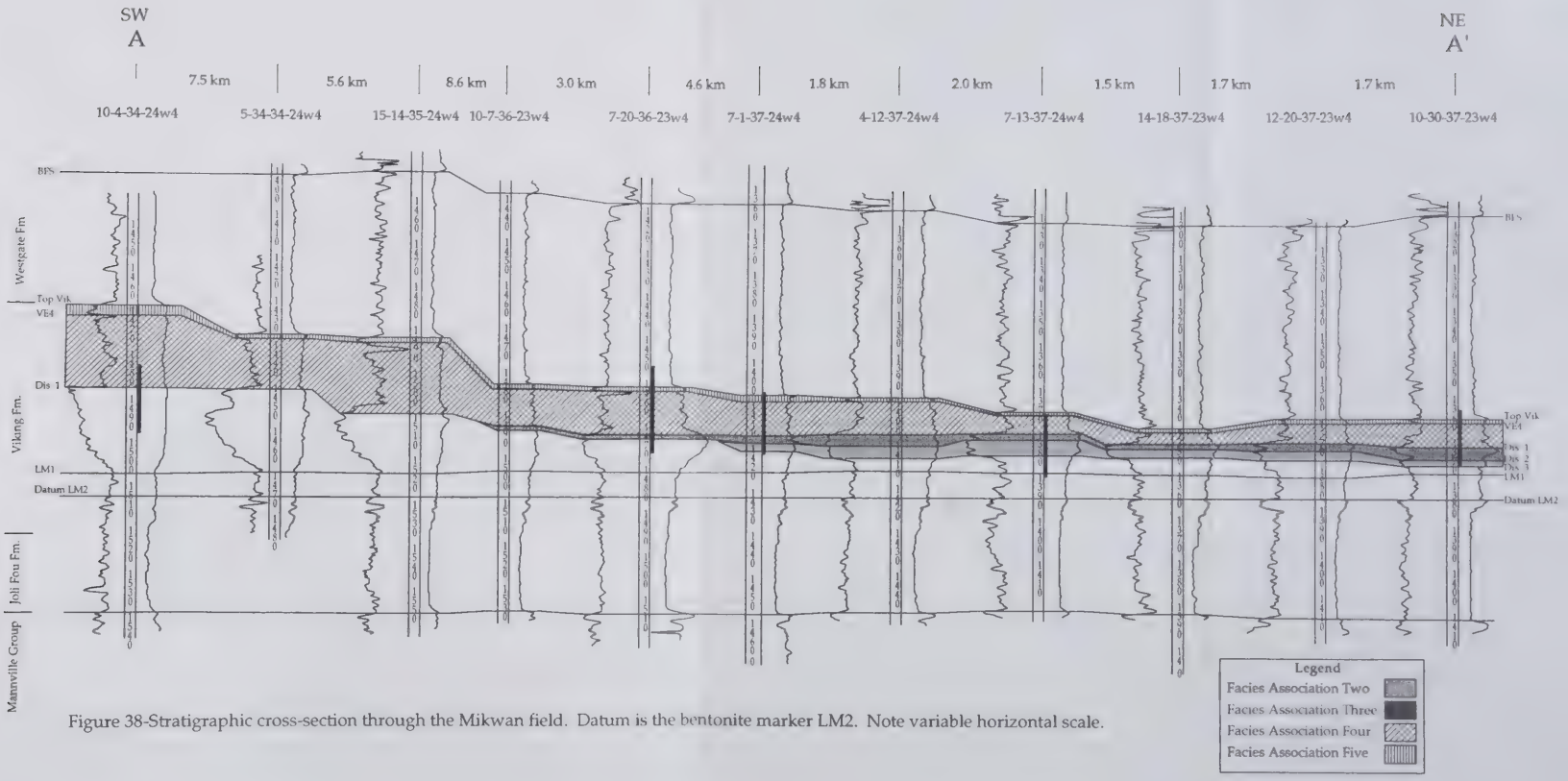


Figure 38-Stratigraphic cross-section through the Mikwan field. Datum is the bentonite marker LM2. Note variable horizontal scale.

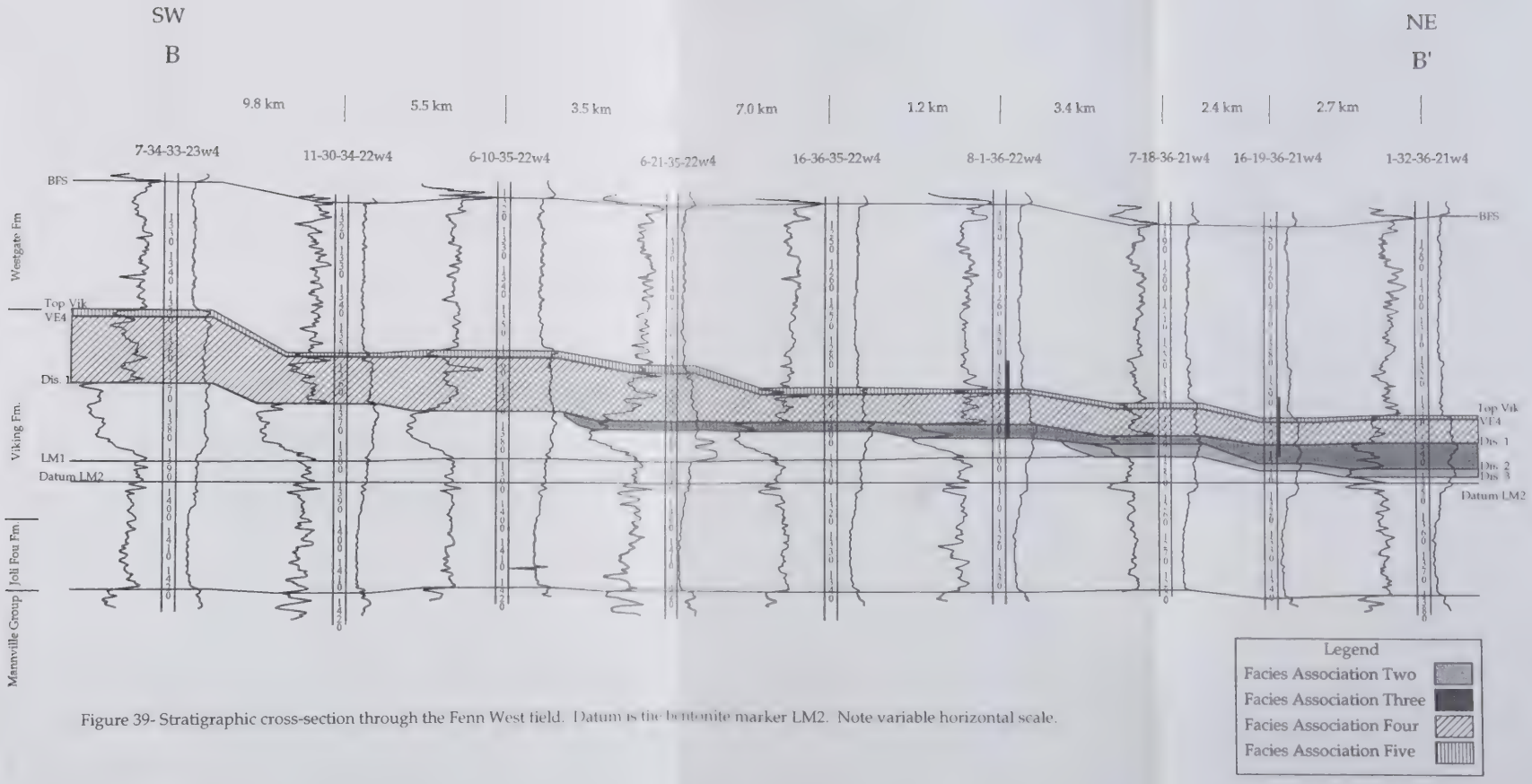


Figure 39- Stratigraphic cross-section through the Fenn West field. Datum is the bentonite marker LM2. Note variable horizontal scale.

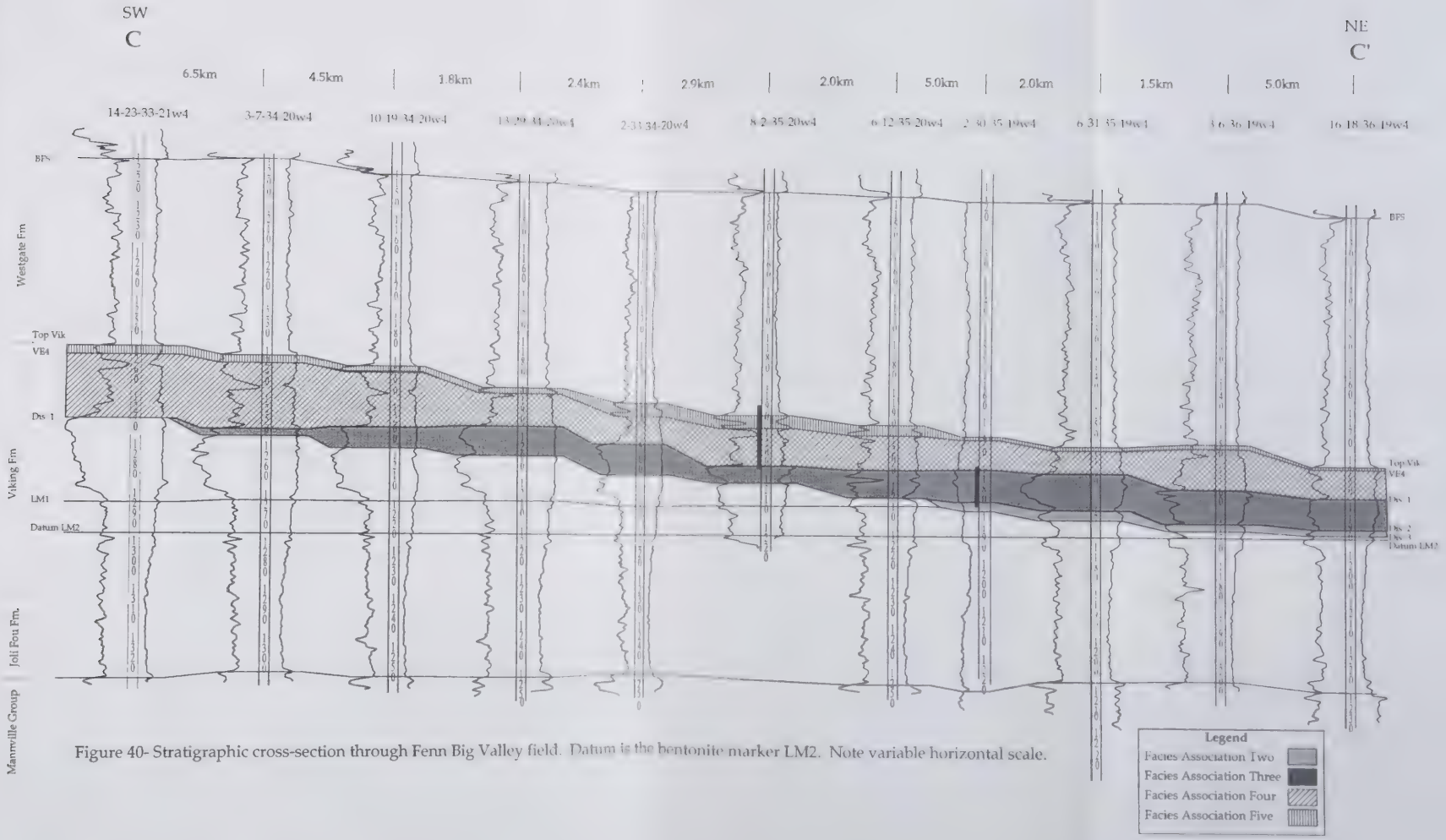


Figure 40- Stratigraphic cross-section through Fenn Big Valley field. Datum is the bentonite marker LM2. Note variable horizontal scale.

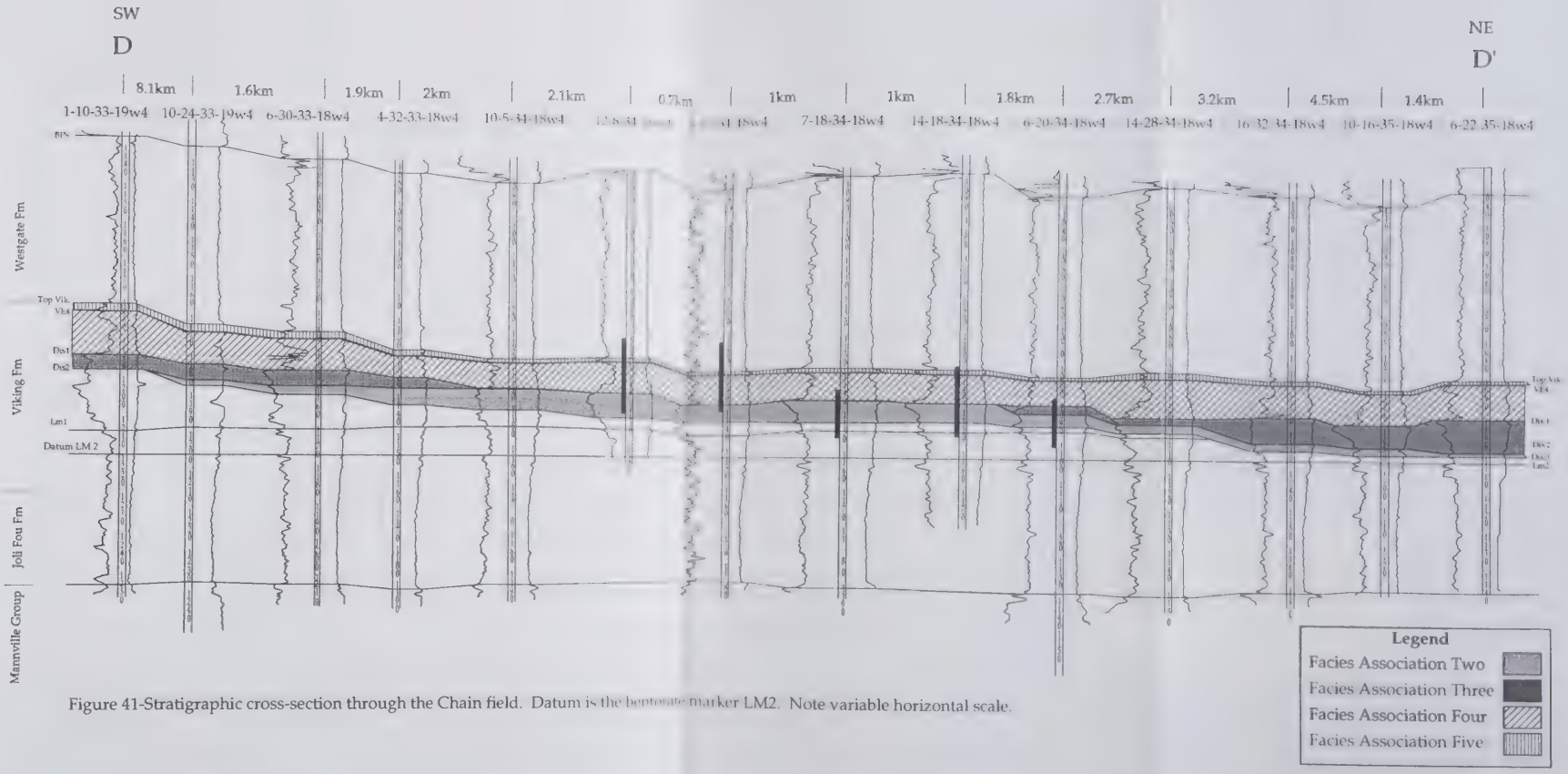


Figure 41-Stratigraphic cross-section through the Chain field. Datum is the bentonite marker LM2. Note variable horizontal scale.

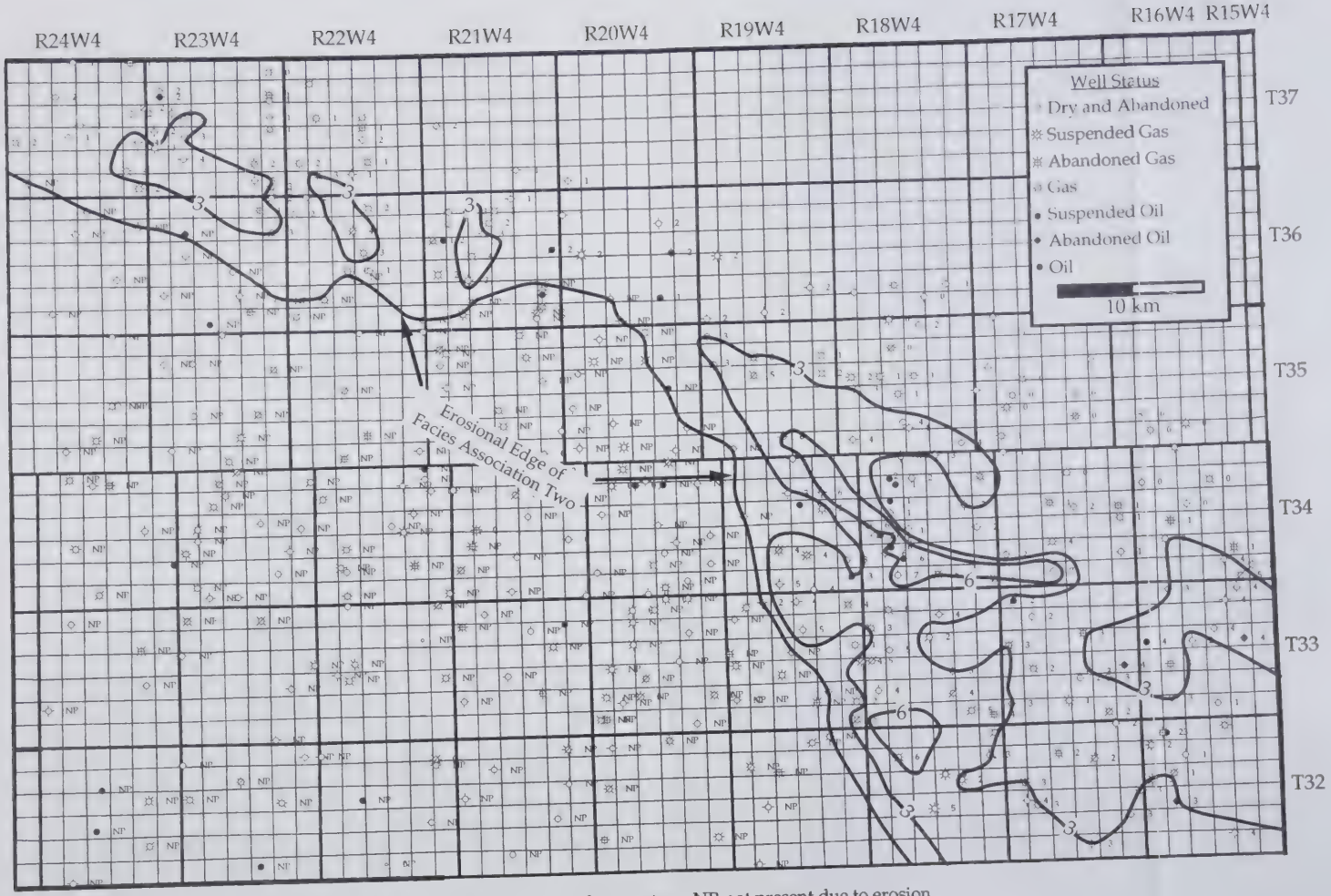


Figure 42-Isopach map of Facies Association Two. Contour interval is three meters. NP-not present due to erosion.

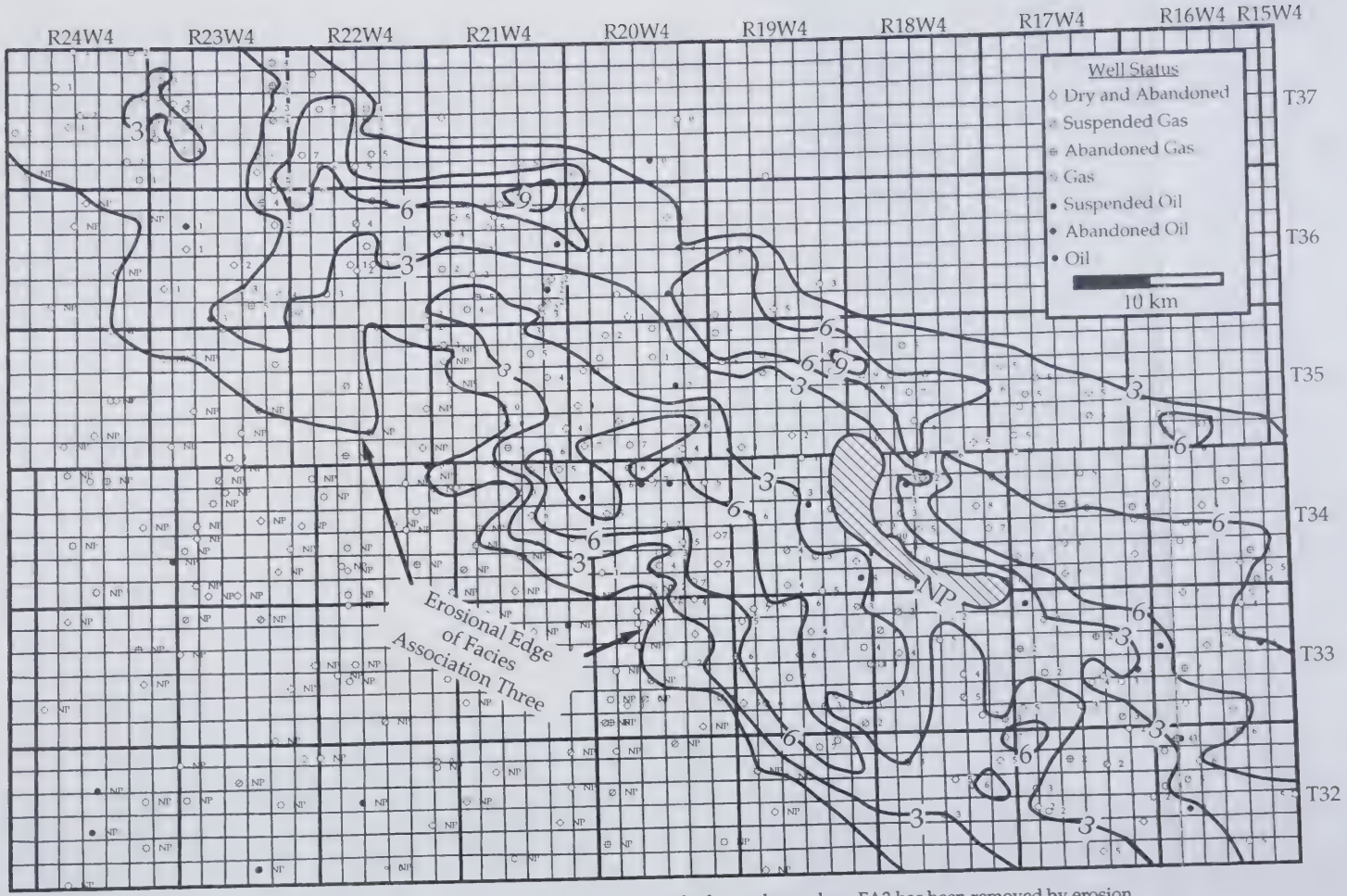


Figure 43-Isopach map of FA3. Contour interval is three metres. NP and cross-hatched area show where FA3 has been removed by erosion.

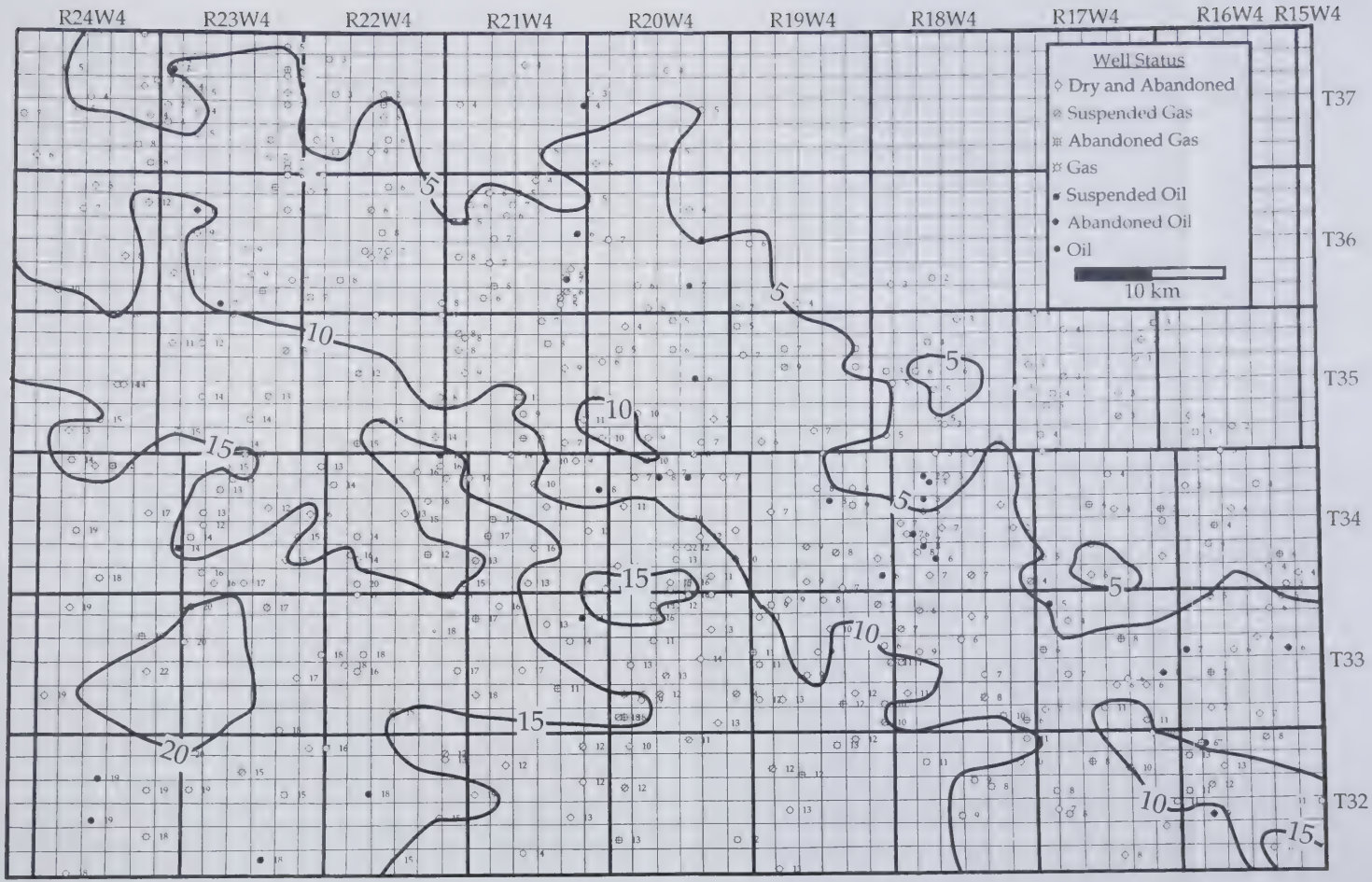


Figure 44 - Isopach of Facies Association Four. Contour interval is five metres.

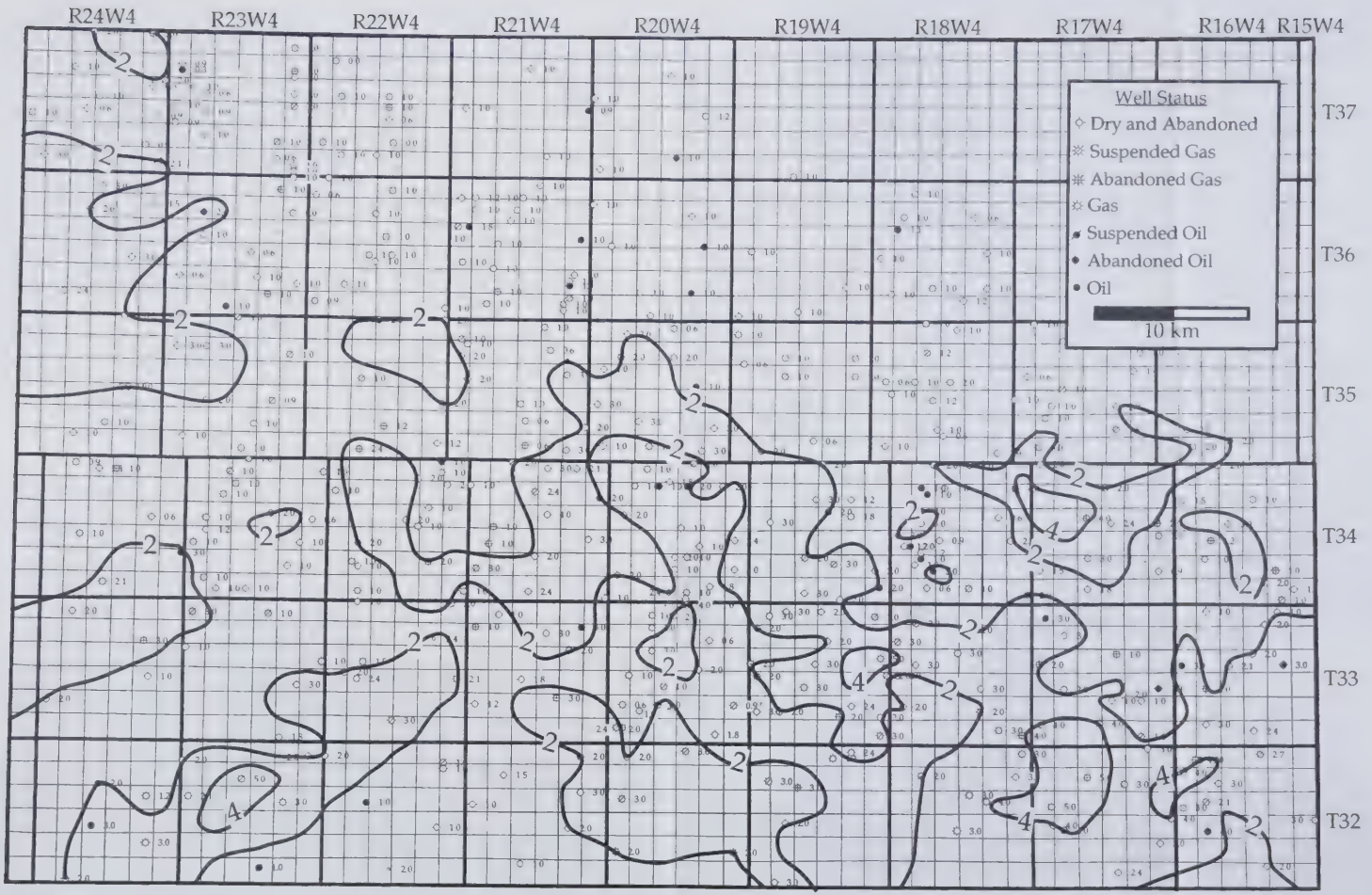


Figure 45-Isopach map of Facies Association Five. Contour interval is two metres.

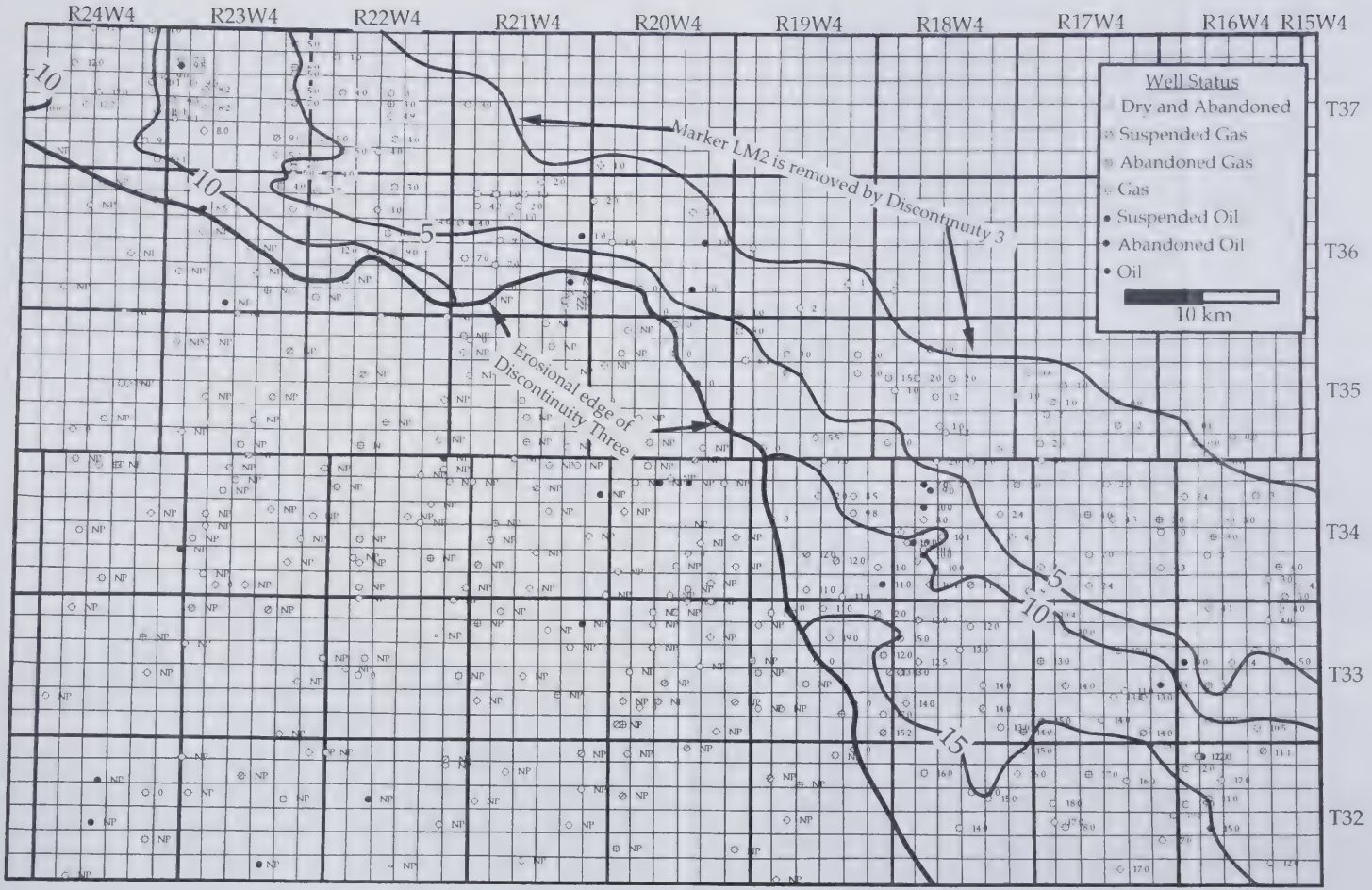


Figure 46 -Isopach from bentonite marker LM2 to the erosional surface, Discontinuity 3 Contour interval is five metres. NP- Not present.

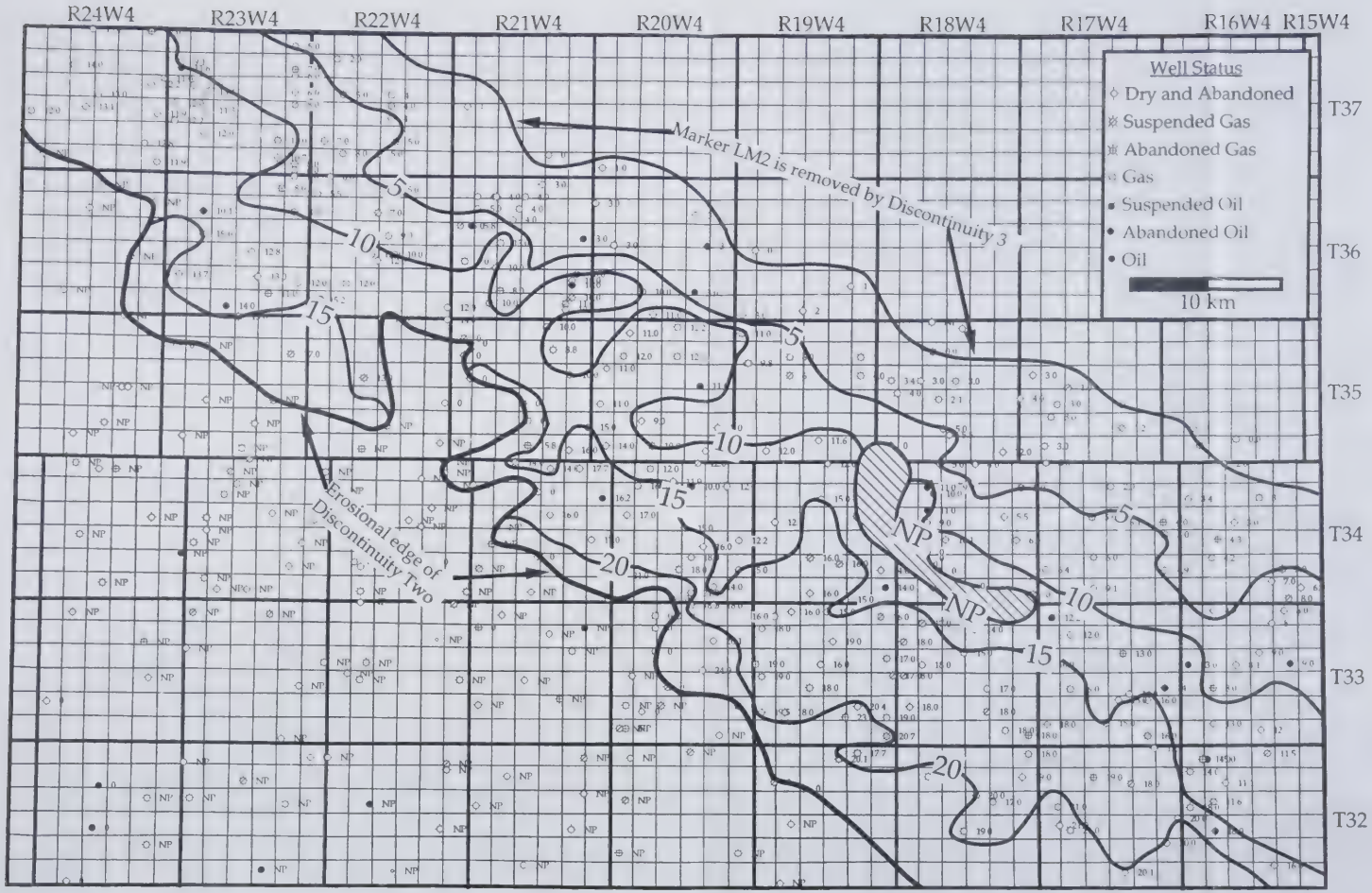


Figure 47- Isopach from the bentonite marker LM2 to Discontinuity 2. Contour interval is five metres. Cross-hatching shows where Discontinuity Two has been removed by Discontinuity 1. NP-Not present.

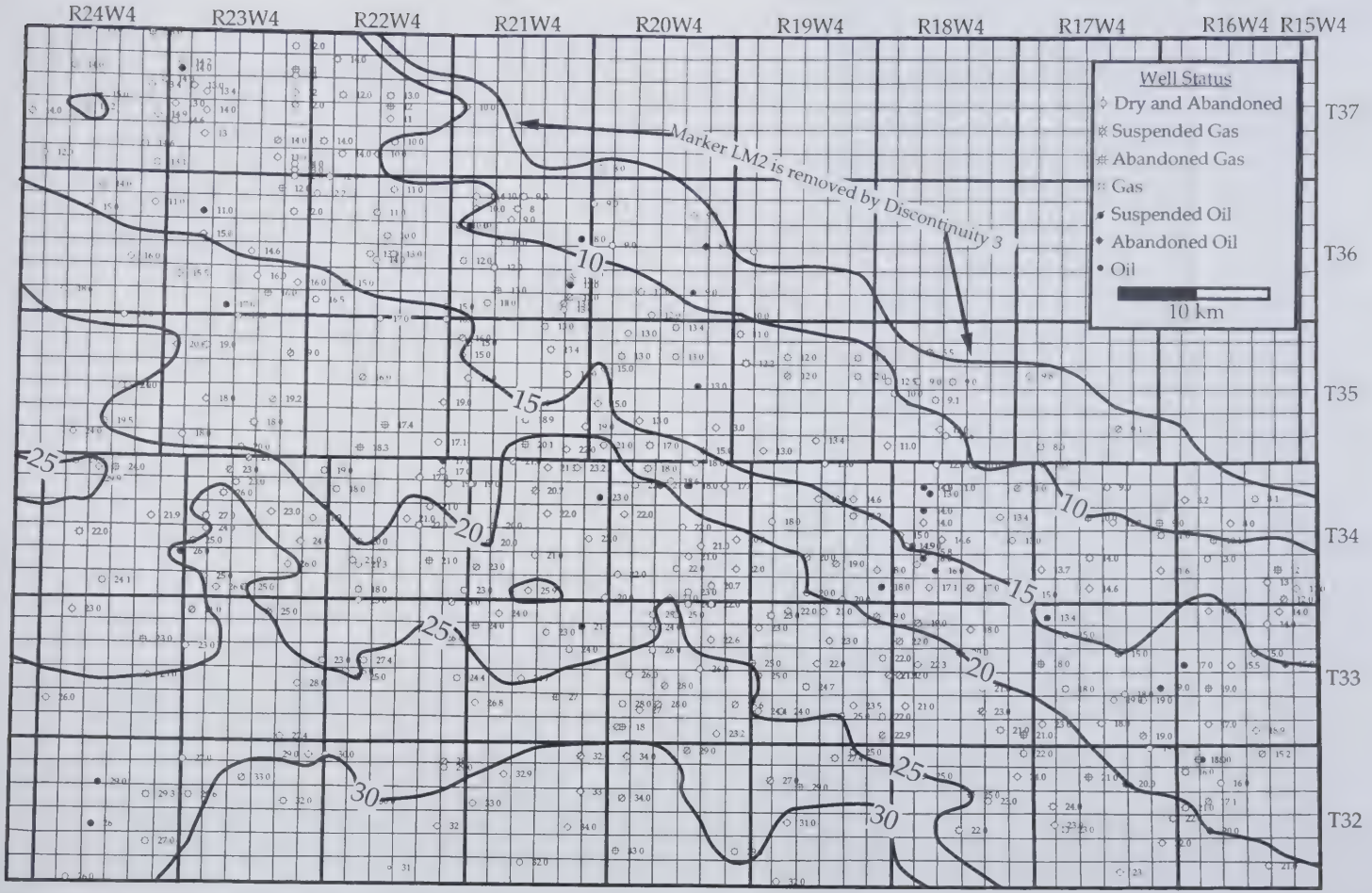


Figure 48-Isopach map from bentonite marker LM2 to Discontinuity One. Contour interval is five metres.

CHAPTER FIVE: INTERPRETATIONS AND CONCLUSIONS

5.1: Introduction

The distributions of facies associations and discontinuities were discussed and illustrated in both a lateral and vertical sense, using cross-sections and isopach maps in the previous chapter. With this information a stratigraphic framework can be established for the Viking Formation in the study area. The Viking Formation is composed of five facies associations, which in turn are bound by five discontinuities or depositional breaks. This chapter offers some possible interpretations on the genesis of the discontinuities and the depositional environments represented by the facies associations.

5.2: Interpretations

Any interpretation that attempts to explain the origin of discontinuities in the study area has to incorporate and honor the observations made in the previous chapters. In the Viking Formation, there are three possible scenarios in which regionally extensive erosional surfaces could have been produced: 1) under fully subaerial conditions, 2) under fully submarine conditions, or 3) under subaerial conditions which were subsequently modified by transgression (Downing and Walker, 1988; Davies, 1990; Hadley, 1992). Interpretations as to the nature and origin of the discontinuities and facies associations in the study area follow, offered in stratigraphic order, starting with FA1, the stratigraphically lowest and oldest facies association.

5.2.1: Facies Association 1

FA1 forms the basal succession of facies in the study area and consists of stacked NW-SE trending regionally extensive parasequences. These parasequences comprise well burrowed successions of lower offshore silty shales grading into lower shoreface muddy sandstones. The parasequences of FA1 form a progradational parasequence set of a highstand system tract. The top of FA1 is erosively truncated by Discontinuity 3.

5.2.2: Discontinuity 3 and Facies Association 2

When examining the nature of Discontinuity 3, any explanation that is presented must account for the following observations: 1) the stratigraphic downcutting of Discontinuity 3 in a basinward direction, 2) the demarcation of Discontinuity 3 in many cored intervals by the *Glossifungites* ichnofacies, 3) the mantling of Discontinuity 3 by a thin pebble or conglomeratic lag, and finally, 4) the erosive nature of Discontinuity 3 where initial deposits overlying it were deposited below fairweather wave base.

The facies of FA2 reflect a medium- to coarse-grained shoreface succession. Proximal sediments of FA2 lie on a conglomeratic lag and display the characteristics of a fully marine, moderately wave-dominated lower to middle shoreface containing a proximal *Cruziana* to distal *Skolithos* ichnofacies. The distal facies of FA2 are dominated by thoroughly burrowed sandy shales of the upper offshore containing a *Cruziana* ichnofacies and dispersed pebbles and granules. That Discontinuity 3 is demarcated by the *Glossifungites* ichnofacies in an offshore position is clear evidence of its erosional nature.

From the perspective of sequence stratigraphy a sharp-based shoreface succession reflects either a forced regression scenario, or stillstand progradation during a transgression (Posamentier *et al.*, 1992; MacEachern, 1994, Walker and Wiseman, 1994; MacEachern *et al.*, 1995b). If Discontinuity 3 reflects a purely lowstand surface of erosion (LSE; Fig. 49), formed during a drop in relative sea level under subaerial conditions, then there should be some evidence of rooting or paleosol development on this surface. No evidence of this has been observed in drill core. Another possibility invokes a variant of the LSE, the forced regression shoreface complex (Fig. 49), in which the lowstand erosional surface forms under submarine conditions. A forced regression shoreface forms during a rapid drop in relative sea level, which brings offshore deposits into the zone of wave erosion (Posamentier *et al.*, 1992). Basinward of this point the LSE changes into a correlative conformity, while in a landward direction the LSE is subaerially exposed. The rapid drop in relative sea level causes a rapid "progradation" or basinward shift in facies, abruptly shifting shoreface deposits into the former offshore realm. Evidence of this in drill core or outcrop is an abrupt change in depositional environments across this surface, typically a shift from basinal sediments below to more proximal facies above. Discontinuity 3 marks a

sharp, primarily lithologic, change from the underlying lower offshore, silty shales of FA1 to the overlying pebbly, muddy sandstones of FA2. Locally, the sediments of FA2 above Discontinuity 3 were deposited in a upper offshore to lower shoreface environment.

It is also unlikely that Discontinuity 3 is a transgressive surface of erosion (TSE) forming under purely submarine conditions. For transgressive erosion to have occurred in offshore deposits, sea level must have lain basinward of that point prior to the ensuing rise in sea level. Further, if Discontinuity 3 had developed solely due to a rise in relative sea level, then the stratigraphic incision of the surface in a basinward direction would be difficult to explain. The substantial relief on the Discontinuity 3 surface would be difficult to produce in a deep water environment.

If Discontinuity 3 is a sequence boundary, then initial offshore deposition below fair weather wave base would overlie a non-erosional surface (correlative conformity; Fig. 49). In contrast, the offshore deposits of FA2 overlie an obvious erosional surface, with dispersed pebbles and a *Glossifungites* suite. The observed features of Discontinuity 3 is best explained as an amalgamated flooding surface/sequence boundary (FS/SB) produced by a combination of the above processes. Development of a FS/SB permits the generation of an erosional discontinuity below stillstand fair weather wave base, because the surface is cut prior to shoreface progradation, while relative sea level lay at a lower stratigraphic level (Fig. 49). A drop in relative sea level caused the initial subaerial exposure and associated erosion of the regional Viking deposits (FA1). Erosion was followed by transgression which removed all evidence of subaerial exposure and shallow water deposits, except perhaps the extensively sideritized top of FA1. The erosion surface produced during this process is termed a transgressive ravinement surface (Nummendal and Swift, 1987), and it served to modify the sequence boundary. During erosive shoreface retreat, a planar ravinement surface is cut, but when a pause in transgression (stillstand) occurs, a bevel or notch may be cut in the surface, prior to progradation of the stillstand shoreface. During this time the fully marine deposits of FA2 were deposited. Discontinuity 3 is equivalent to FS/SB1 of MacEachern *et al.*, (1995) and E1 of Downing (1986.)

5.2.3: Discontinuity 2 and Facies Association 3

Any explanation for the origin of the Discontinuity 2 surface must explain the following observations: 1) the stratigraphic incision of Discontinuity 2 in a basinward direction and its "step-like" rise in a landward direction, 2) the development of shales and silty shales immediately above this surface, and 3) the colonization of the discontinuity by the *Glossifungites* ichnofacies.

For the same reasons that were outlined for Discontinuity 3, it appears unlikely that Discontinuity 2 represents either a purely LSE or TSE. It is evident that Discontinuity 2 developed in the same manner as did Discontinuity 3, and represents an amalgamated FS/SB. The "step-like" morphology of Discontinuity 2 was formed during periodic stillstands during an overall transgression. Discontinuity 2 is equivalent to E2 surface of Downing (1986) and the FS/SB2 of MacEachern *et al.*, (1995b) at Joffre.

Explaining the origin of the deposits of FA3, which overlie Discontinuity 2, is problematic. For reasons mentioned in Chapter Three, it is doubtful that FA3 was deposited as part of a shoreface complex, under fully marine conditions. Equivalent deposits at Joffre were interpreted as conglomeratic shoreface deposits by Downing and Walker (1988). The following features of the FA3 deposits, such as: 1) glauconitic sandstone with mudstone beds and interlaminae, 2) coarse-grained clastics ubiquitously trough cross-bedded, 3) the preservation of abundant non-resistant mudstone clasts, and 4) the interfingering relationship with mudstones and sandstones containing a low diversity trace fossil suite, are inconsistent with that interpretation.

Recent research at Joffre has raised similar concerns with the previous interpretations (MacEachern *et al.*, 1995b). There, the thicker cross-bedded sandstones at Joffre show fining upwards cycles in the coarse-grained facies and an unidirectional character to the cross-beds, all features more typical of channelized deposits than upper shoreface deposits. The sandstones at Joffre pass abruptly basinward into stressed, dark mudstones (MacEachern *et al.*, 1995b). The entire facies succession at Joffre is interpreted to have been deposited in a marginal marine setting by tidal creeks and channels transporting fluvially supplied coarse-grained clastics to a sheltered embayment, concentrating sandstone and conglomerate in a coarse "apron", which interfinger with embayment mudstones (MacEachern *et al.*, 1995b).

The deposits of FA3 in the study area are very similar to equivalent deposits at Joffre. FA3 is interpreted to be the distal equivalent of these deposits which explains the thinner deposits of cross-bedded sandstones in the study area. It is apparent that FA3 was deposited in a restricted marine, tidally-influenced environment, such as in an embayment, protected from fully marine conditions. Though there is no direct indication of a embayment, such evidence may easily have been removed during subsequent ravinement, which generated Discontinuity 1.

5.2.4: Discontinuity 1 and Facies Association 4

Like Discontinuity 2 and Three, Discontinuity 1 rises stratigraphically landwards in a "step-wise" manner, and is demarcated by the *Glossifungites* ichnofacies, albeit rarely. However, unlike Discontinuity 2 and 3, Discontinuity 1 does not stratigraphically downcut in a basinward direction.

Because of this important distinction, Discontinuity 1 in the study area is interpreted as a purely transgressive ravinement surface, rather than a FS/SB. The development of a pebble or conglomeratic lag above Discontinuity 1, overlain by interbedded offshore shales of FA4 is consistent with the cutting of a transgressive ravinement surface and subsequent deepening. Discontinuity 1 represents a major transgression which terminated the deposition of the underlying deposits of FA3. The "step-wise" morphology of the Discontinuity 1 surface was produced by periodic stillstands, during an overall transgression, but apparently not of long enough duration to permit stillstand shoreface progradation.

The facies of FA4 reflect fully marine offshore deposition, with a well developed *Cruziana* ichnofacies, contrasting markedly with the mudstones of FA3. The presence of dispersed pebbles throughout FA4 probably attests to ongoing transgressive ravinement landward of the study area.

5.2.5: VE4 and Facies Association 5

VE4 is widespread throughout the subsurface of Alberta and Saskatchewan and probably represents a regional sequence boundary, which was modified in a "step-wise" fashion by incremental transgression. As such, at a basin-wide scale, VE4 likely is probably a composite surface, made up of a number of discrete FS/SB's. The VE4 surface has the following characteristics that must be explained: 1) like Discontinuity 3 and 2, VE4 stratigraphically

downcuts in a basinward direction, removing an underlying bentonite marker, 2) VE4 is commonly demarcated by the *Glossifungites* ichnofacies, and 3) VE4 is commonly mantled by a conglomeratic lag and transgressive sheet sandstones of FA5.

The portion of the VE4 surface within the study area is interpreted to represent an amalgamated FS/SB for the same reasons given for Discontinuity 3. VE4 is a surface of regional extent and likely represents a basin-wide fall in sea level, followed by a incremental but regional transgression, ultimately associated with the Colorado flooding surface and widespread deposition of the Westgate Fm marine shales. Transgressive ravinement has removed all evidence of subaerial exposure of VE4 in a landward direction. Basinward, FA5 thins dramatically, and VE4 is mantled by only a thin pebble veneer.

5.2.6: Colorado shale flooding surface and the Westgate Fm

The Colorado flooding surface constitutes the last erosional surface, capping the Viking Fm deposits in the study area and signals the onset of basinwide transgression. This surface is characterized by a mantle of conglomerate or a pebble lag, passing into the thick marine shales of the Westgate Fm.

5.3: Depositional history of the Viking Fm in the study area

Following the regional transgression of the Joli Fou Sea, sediment supply from the south and the west permitted distal parasequences (FA1) to prograde and downlap onto the marine shales of the Joli Fou Fm. FA1 is characterized by a number of these internal flooding surfaces, but overall each parasequence prograded further into the seaway, generating a progradational parasequence set of a Highstand System Tract.

At some later stage, a relative fall of sea level shifted the shoreline further to the northeast, possibly as far as Joarcam (*cf.* Posamentier *et al.*, 1992), and generated a regional sequence boundary which incised into FA1. A subsequent rise in relative sea level permitted the transgressive modification of this sequence boundary by ravinement during erosional shoreface retreat, generating Discontinuity 3, and permitted its colonization by a *Glossifungites* suite. A stillstand in the rate of transgression led to the formation of a bevel,

or notch in Discontinuity 3. A fully marine incised shoreface complex prograded out across this FS/SB during stillstand, constituting FA2.

A relative fall in sea level incised a sequence boundary into FA2, and subaerially exposed it, manifest by the high degree of siderization prevalent in the underlying facies. A subsequent transgression ensued, which modified the surface and allowed it to be colonized by a *Glossifungites* suite (generating Discontinuity 2). Tidal creeks and channels transported fluvially supplied coarse-grained clastics, forming a clastic "apron", which prograded into a sheltered embayment, constituting FA3.

Resumption of transgression led to the development of a ravinement surface designated Discontinuity 1 which rises in a "step-wise" fashion to the southeast, cutting into FA3, FA2 and FA1 and generating Discontinuity 1. FA4, which overlies Discontinuity 1, reflects deposition in an offshore setting.

A relative fall in sea level generated a regional sequence boundary which incised into FA4. Incremental transgression modified the sequence boundary, generating the VE4 surface. Above VE4, poorly-sorted sandstones and conglomerates associated with transgressive ravinement were deposited, constituting FA5.

A resumption in transgression led to the formation of the Colorado flooding surface, which terminated Viking Fm deposition in the study area. The surface reflects basin wide transgression, manifest by the deposition of marine shales of the Westgate Fm.

5.4: Conclusions

1. The Viking Formation in the study area can be differentiated into five recurring facies associations (FA1 to FA5). These facies associations are bound by five erosional discontinuities of sequence stratigraphic significance.

2. Three of these discontinuities, Discontinuity 3, 2 and VE4 are interpreted to be amalgamated flooding surfaces and sequence boundaries (FS/SB). Discontinuity 1 and the Colorado flooding surface are interpreted as purely transgressive ravinement surfaces

3. Each of these facies associations, defined by the erosional discontinuities, is an allomember and the vertical and lateral distributions of these allomembers can be mapped in the study area on the basis of core and geophysical well log characteristics.

4. FA1 constitutes a fully marine progradational parasequence set of a Highstand Systems Tract and corresponds to Regional Viking deposits. FA2 is interpreted to have been deposited as fully marine incised shoreface deposits on the Discontinuity FS/SB during a stillstand in transgression. FA3 was deposited as a salinity stressed sheltered embayment complex on the Discontinuity 2 FS/SB. FA4 accumulated in fully marine offshore conditions on the Discontinuity 1 ravinement surface during a resumption of transgression. FA5 was represents a ravinement lag, developed on the widespread VE4 FS/SB surface..

5. Discontinuities 3 and 2 form steep one-sided bevels on which overlying deposits of FA2 and FA3, respectively, have accumulated.

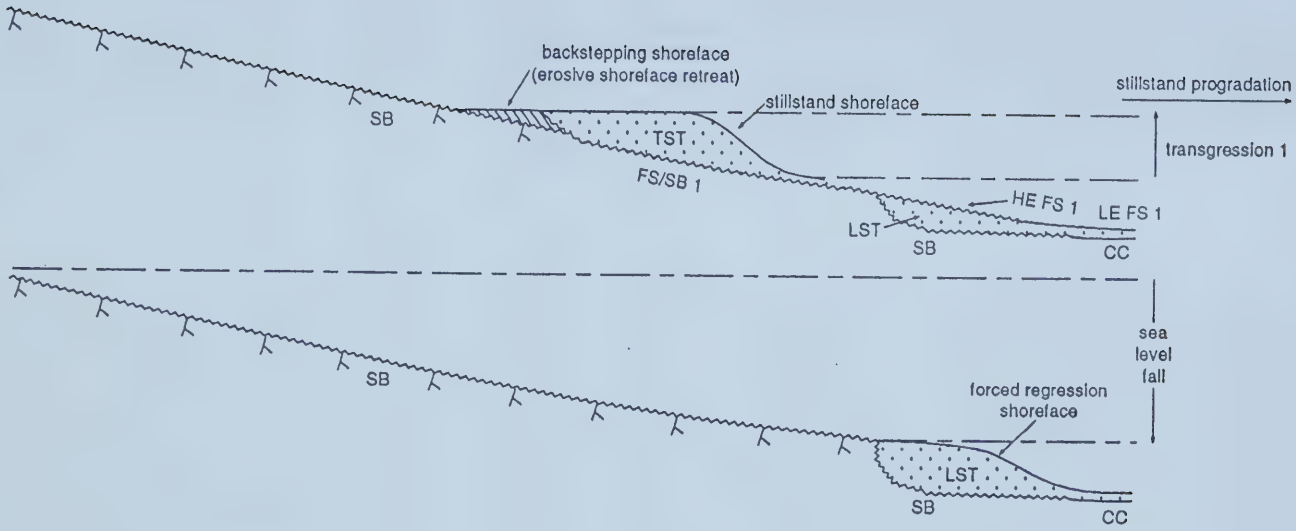


Fig. 49-The two types of sharp-based incised shoreface settings. The top diagram shows stillstand progradation during transgression, while the bottom diagram illustrates a forced regression scenario. Modified after MacEachern (1994)

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